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COMPREHENSIVE STUDIES OF SOLID WASTE MANAGEMENT

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COMPREHENSIVE STUDIES OF SOLID WASTE MANAGEMENT

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Third Annual Report

COMPREHENSIVE STUDIES OF SOLID WASTE MANAGEMENT

Third Annual Report

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FOREWORD

At the time of passage of the Solid Waste Disposal Act (PL 89-272) in 1965, few, if any, studies of a truly comprehensive nature had been undertaken to develop solutions to problems in all aspects of solid waste management. Although earlier research studies have made invaluable contributions to knowledge in the field, they tended to focus primarily upon discrete facets of the total solid waste problem.

The present report represents the continuation of the first major effort to examine the solid waste problem from the standpoint of systems analysis. An overall solid waste generation and evaluation model was developed, demonstrating interrelationships between land use, technology, economics, population, and other system elements. Practical implications were drawn from this model, as they relate to planning, public health, and application of technology.

A further example of the systems approach to solid waste management is given in the final report of a Solid Waste Management demonstration project, *A Systems Study of Solid Waste Management in the Fresno Area* (Public Health Service Publication No. 1959).

--RICHARD D. VAUGHAN
Assistant Surgeon General

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I. INTRODUCTION

NEED FOR STUDY

Need for comprehensive studies of solid waste management such as herein reported is the natural outgrowth of a traditional American unconcern for the conservation of resources and an unconscious indifference to what is now called "the environment." The result, described in greater detail in the first of this series of annual reports [4], was that each local jurisdiction called upon technology to perform only the most rudimentary of tasks—pick up, haul, and deposit—until human communities became so complex that even these simple tasks were all but impossible. The collection system became uneconomical by any comparative standard, traffic and transportation made hauling difficult, no plans for unloading inside the boundaries of the jurisdiction had been made, and neighboring land areas faced the same unsolved problems. Moreover, the effect of urbanization of human society spilled over onto land beyond the city's limits. This led to attempts to control the environment by zoning and limited piecemeal land-use management measures which constrained the freedom of decision of private enterprises and so caused industrial, agricultural, and commercial solid wastes to join municipal refuse as a matter of public concern and responsibility. Burning to reduce volume of wastes was found to be at best a primitive process when concern for the air resource was thrust into the problem of environmental quality.

Within a rather brief period of time society became uneasy over the possible consequences of resource exploitation and of the impact of man on his own environment. It became painfully clear that in the matter of solid waste management no one really knew how much of what is present in solid wastes or where it occurs in the community; the resource potential of wastes had not been evaluated; technology had never been asked to solve any of the emerging problems within an environmental or conservation framework; society was organized to deal with regional problems only on a fragmented local basis, and was institutionalized to deal with the quality of air, water, and land resources as discrete and essentially unrelated problems; systems had emerged historically from sheer probability, or improbability; and the public, although showing signs of concern for the environment or a high conceptual plane, had little regard for their own solid waste nor applause for those who took care of it. Clearly there was a need for bringing together a team of planners, economists, health specialists, systems experts, engineers, and technologists to explore ways to overcome in a systematic and organized fashion the consequences of overlong neglect of the problems associated with "solid wastes."

During the period covered by the report herein presented, several changes occurred relative to the need for study. For the most part they served only to increase the urgency of the need, but in a few cases a change in emphasis emerged. On the national scene citizens tended to group solid wastes with air and water pollution problems in a single category of insult which defiles the "total environment." Concern for the total environment led directly to concern for the ecosystem of nature, and so the public came to ascribe to solid wastes a greater role than it merits in damaging the "ecosystem." This added to the problem of solid wastes an aura of crisis, the effect of which is not yet clearly evident. It did, however, heighten the concern of citizens for the effect of man on the environment. Taking a more realistic approach, most public agencies gave first priority to the effects of environment on man. In this context the aspects of the solid waste problem outlined in preceding paragraphs came into sharp focus and raised the immediate question of whether a need for study was secondary to a need for action. This question immediately generated another question: "What are the attainable goals of action?" If technology is to be asked to do rudimentary things – pick up, transport, and deposit – there is but limited progress that can be made by action toward solving the solid waste problem in an environmental and resource context. This self-evident and unsatisfactory answer made more urgent a need for practical technological solutions of a more sophisticated nature. The response was a rash of simplistic solutions by 'far out' new concepts which during the year herein reported lost much of their luster when confronted with the complexities and realities of the solid waste problem. Thus was emphasized a need to discern more clearly what action is necessary and to be cognizant of research on new technologies.

Both citizen and official objectives of resource conservation and environmental control generate a need for recycling of resource value. Thus there is still a need at this late hour to find out how much of what resource is being wasted; at what point in time will wastage of one resource value cease in favor of wastage of another; and when on a time scale will certain residues become valued as resources. Associated with this question is that of the technology of recycle of some resource values. Here a need for study exists in the case of some materials and for action in the case of others. An overall need therefore exists for asking technology to do more sophisticated things, and it can be argued that research on some of the traditional techniques needs de-emphasis in favor of that related to resource recycle. Here the need for study is urgent.

In the realm of jurisdictional and institutional arrangements, the problems are well recognized. The need for action is clear, but how that action can be brought about within existing political, social, and cultural constraints is still in need of study.

Based on the foregoing analysis and rationale it is concluded by the authors of the report herein presented that the need for action resulting from neglect of the problem of managing solid wastes until it reached crisis proportions, makes more urgent, rather than redundant, a need for study of jurisdictional, planning, economic, and systems managements as a blueprint for action; and generates a need for technological research along the road to recycling rather than destroying resource residues.

OBJECTIVES OF STUDY

Pursuant to the rationale set forth in the Need For Study, the general objective of the study was to make a significant contribution to a resolution of the problems which created the need, through a multidiscipline research program. Pursuant to this general goal, the research program herein reported was directed to several more specific objectives. As noted in the Second Annual Report [1] these included:

1. To bring the competence of people in the wide variety of disciplines involved in planning, financing, and administering a community into effective combination with that of engineers and environmental health specialists in seeking solutions to problems in solid wastes management which are technically sound, economically feasible, and politically and socially acceptable.

2. To bring the techniques of modern operations research to bear upon the organizational problems of managing solid wastes on an areawide or communitywide basis; and on the physical and logistic problems of collecting, transporting, and disposing of wastes.

3. To seek through experiments and other research techniques improvements in conventional methods of wastes disposal and the development of new procedures for reclaiming or recycling fractions of the refuse mass.

4. To identify and seek answers to problems involving man's health and well-being that may be associated with solid wastes and related to his use of land, water, and air resources.

5. To develop, through participation in research, greater understanding and knowledge on the part of engineers, planners, administrators, economists, public health specialists, and others who are confronted with the problem of solid wastes management in the course of their professional service to the modern urban-industrial-agricultural community.

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6. To insure, through close coordination and effective communication with public and private agencies, the pertinence of research to real problems and the prompt availability of the results of research to professional practitioners.

ORGANIZATION FOR STUDY

Five faculty members, namely Professors P. H. McGauhey, I. B. Tabershaw, B. D. Tebbens, S. A. Hart, and W. J. Kaufman, representing the Sanitary Engineering Research Laboratory of the College of Engineering and School of Public Health on the Berkeley Campus and the Department of Agricultural Engineering on the Davis Campus of the University of California, were initially responsible for the overall management of the project. However, on 1 July 1969 Professor P. H. McGauhey retired from the University and thereafter served only in an advisory capacity. He was replaced as Principal Investigator of the Project by Dr. Clarence G. Golueke, Chief Biologist of SERL and Coordinator of the study since its inception. In the conduct and coordination of the research program he was assisted by additional faculty members and professional research personnel who took responsibility for various specific aspects, including:

Professor C. R. Glassey	Operations Research
Dr. S. A. Rao	Planning and Economics
Dr. D. L. Brink	Forestry
Professor C. R. Wilke	Chemical Engineering
Professor P. B. Stewart	Mechanical Engineering

Mr. Stephen A. Klein divided his time between assistance to Dr. Golueke and conduct of research on the anaerobic digestion of solid wastes. In the 1969-1970 period a total of 18 graduate students participated in the program.

→ Reviewed are the following topics

AUTHORSHIP CREDITS

Authorship credit for individual chapters of the report is due the following participants in the project:

Need For Study - P. H. McGauhey

Planning and Economics - S. A. Rao

Operations Research - H. Stern, A. Nigam, E. Lofting, and C. R. Glassey

Anaerobic Digestion - S. A. Klein and D. B. Chan

Biological Fractionation - R. Rosenbluth, G. Mitra, and C. R. Wilke

Wet Oxidation - J. Bicho and D. L. Brink

Pyrolysis-Combustion - D. L. Brink

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II. PLANNING AND ECONOMICS

REVIEW OF WORK TO DATE-OBJECTIVES AND RATIONALE

Since the writing of the Second Annual Report [1], the research work of the Planning and Economics team has been directed toward the achievement of substantive progress in several phases of its intended activities. Thus the primary goals and specific objectives have been brought under sharper focus in the light of experience gained in the past three years. This, in turn, has made it possible to assess realistically the potential of laudable goals and of their implications in terms of practical applications, and thereupon to identify various research aspects which could be of benefit in attaining the goals of the project as a whole.

After carefully examining the original plans, the major objectives discussed in the succeeding paragraphs were formulated as a basis for evaluating progress made thus far, as well as for setting up a definite plan of action for future research into various economic and practical aspects which have hitherto received only peripheral treatment.

Development of Structural Models for Studying the Existing Relationships Among Various Types of Solid Wastes Generation and Relevant Economic, Demographic, and Land-Use Information

Initially, the model formulation consisted of defining various types of solid wastes and constructing the analytical framework for studying each type of waste in relation to pertinent economic variables such as population, income, employment, and land use. The analytical framework was to be in the form of a multiple regression in which solid waste volume would be treated as the dependent variable and be regressed against the set of independent variables. The model would then be able to specify the structural relations between specific types of solid wastes and the generators of wastes. However, as the research progressed, it became clear that such an approach was too idealistic, and that an alternative method had to be developed. The problems responsible for the need to change the approach were mainly twofold: 1) large quantities of solid wastes (mostly industrial and commercial) were not accounted for, primarily because they do not enter the regular disposal sites, and 2) the estimates of wastes received at the disposal sites could not be related to comparable sources of wastes, thus precluding a thorough analysis of waste quantities coming into the sites. Subsequently, the limitations imposed by these two problems were delineated and alternative approaches were developed to circumvent the limitations. The results obtained in this portion of the work were given in the Second Annual Report.

Inasmuch as the development of a waste generation model is a continuous process, refinement and expansion of the present model is an ongoing part of the research. The research procedure consists mainly of recognizing the interindustry details of the study region, wherein it is possible to recognize waste management industry as one of the producing and consuming sectors in the overall economic study of the region in question.

Development of Procedures to Estimate Pertinent Quantities of the Various Types of Solid Wastes Generation Through Definition of Appropriate Sources of Wastes (Generator) and Corresponding Spatial and Functional Boundaries with Reference to a Selected Study Area

The utility of the analytical framework depends to a large extent on availability of consistent and comparable data on the volume of solid wastes generated and on other related variables. Inasmuch as the available body of data on solid wastes could not be successfully related to other variables, a beginning was made by listing waste generators, estimating waste multipliers, and obtaining data on population, employment, and land use on a functionally comparable basis, while at the same time avoiding duplications or omissions. Work done along these lines in the present research period was successful in its outcome, and was reported in the Second Annual Report. It was possible to identify more than 30 different sources of wastes, making it possible to develop adequate relationships between waste generation and generators both for descriptive and forecasting purposes. With the procedure established thus far, it was possible to take into account nearly all types of solid wastes (domestic, commercial, industrial, and agricultural) generated in a community, and thereby arrive at a realistic evaluation of the magnitude of the problem. The research work done in accomplishing this objective gave rise to the concept of "functional boundaries" or "disposal service areas." This concept was used extensively in setting up a much-needed empirical data base for making the quantitative analyses needed in the work concerned with the study region (i.e., the nine-county San Francisco Bay Area).

Development and Improvement of Solid Waste Multipliers and Their Composition by Detailed Levels of Economic Activity and Waste Sources

The estimation procedures developed in the pursuit of the preceding objectives led to a recognition of separate waste multipliers per unit of waste source in the nine-county study region. Though the concept of waste multipliers itself is not new, a brief survey of existing literature indicated a conspicuous absence of useful estimates of such multipliers for developing quantities of waste generation in a given community.

During the previous years of the research much work was done in developing waste multipliers on the basis of available sample studies carried out in the study region. These multipliers were incorporated in estimates of waste generation in the nine-county study region. Present plans call for improving the quality of these multipliers by making a detailed examinatiin of the physical and chemical composition of the wastes, and by comparing these multipliers with those obtained in other regional studies, such as the Des Moines Metropolitan Area Solid Wastes Study [2] and the Fresno Area Solid Wastes Study [3]. Such a study of waste multipliers can be used to verify the accuracy and relevance of the quantitative estimates developed earlier in this study and also to provide guidelines for other similar studies. The substantive progress made in the study of waste multipliers was not complete at the time of writing this report, and will be reported in a future presentation.

Survey of Engineering and Economic Aspects of Current Methods of Transfer and Disposal of Solid Wastes

Progress already has been made in this direction and is reported in the Second Annual Report. The research reported in the Second Annual Report consisted of discussions of each of the following technologies: anaerobic digestion, composting, wet oxidation, incineration-pyrolysis, and biological fractionation. A systematic comparison of engineering aspects, cost considerations, economies of scale in the operation of each of the above disposal methods and the trade-off between transfer and disposal is considered for present and future work. This phase of the research will of necessity be preceded by work in other closely relevant areas such as cost of transfer and transfer stations, cost of by-products of the processes (whether positive or negative), and of other related items. The end product of this phase of work will be sufficiently complete and detailed to permit a listing of realistic alternative solutions (or combinations of processes) for use in developing an overall systems analysis approach.

A detailed approach to achieve the above objective will involve an elaborate treatment of the subject in which will be defined appropriate production and related cost functions for each method of disposal or transfer. It will also be necessary to identify those subprocesses within each listed process which are subject to differing variation in costs as the scale of operation increases. The available body of information suggests that the multiple regression technique could be effectively used in some cases to estimate relevant parameters influencing the costs of disposal and transfer.

In the present report a brief survey of existing and experimental techniques of disposal is attempted with a view of establishing a framework for the study of the economic implications of each method on a comparative basis. Conventional methods receiving attention are landfill, incineration, and composting. Experimental methods to be considered are compaction, wet oxidation, anaerobic digestion, and biological fractionation. Each method is discussed in terms of process, required equipment, possible by-products, and costs of operation. In the case of landfill, a detailed account of the method of estimating cost variation is given. The experimental techniques are discussed summarily.

Analysis of Private and Public Expenditures in the Solid Wastes Industry—Theoretical and Empirical Issues with Reference to a Metropolitan Region

An important element in formulating and implementing an effective wastes management system is the consideration of current expenditures on different segments of the waste management program, and the changes in expenditure suggested by proposed alternative management procedures. Specifically, the expenditures are incurred by private households, industry, commerce, and agriculture as consumers using the waste disposal facilities. In addition to this, expenditures are incurred by public bodies as a part of supervision and administration of waste management programs. Because of a variety of ways in which portions of solid wastes generated in the community are handled, there is a great need for establishing detailed accounting and estimation procedures by means of which it would be possible to estimate true costs of the several functions of waste management within the community.

A detailed cost structure, as it currently exists, should have many uses. For example, it would be of value in comparing the efficiencies of various systems. With it, one could estimate costs of alternative methods proposed for future implementation. In a larger sense, data available on expenditures by public and private agencies should be sufficient as a basis for discussing the present distribution of costs, efficiency, and equity criteria.

The initial phase of this objective was to recognize the different ways in which wastes can be handled, e.g., wastes can be handled by any or all of 12 different combinations of agencies and functions, viz., collection and hauling transportation, and supervision and administration of disposal by private or public agencies. Details were given in the Second Annual Report. Private agencies can be either franchised scavenger companies or commercial haulers. Disposal site operations can be conducted either by private companies or by public agencies. Each one of the various possible combinations of agencies and functions poses unique problems to be overcome in arriving at estimates of the true cost structure of a subsystem. Although some progress was made and was reported in the Second Annual Report, much analysis remains to be carried out. It is planned to discern the various difficulties inherent in the estimating procedures and to develop reliable estimates with reference to smaller study regions. At present, the Oakland metropolitan area in California is considered as one such region. It contains all of the complexities, and yet such a study could be completed within a reasonable span of time.

A detailed report on the progress made to date on the study of theoretical and empirical issues with reference to the Oakland metropolitan region is given later in this report.

Application of Network flow Model for Finding Short-Term Solution Assuming Landfill as the Ultimate Disposal Method

As mentioned previously, the planning and economics team is working with the operations research team in providing empirical data for the overall model, and in turn is using the submodels developed for feedback within the overall research team. An outgrowth of this joint venture is the development and application of a network flow model for re-routing solid wastes from generation points to disposal sites. It is assumed that in the short run (i.e., a span of 5 years) the overriding disposal method would still be landfill, and the overall waste management problem could be considered as one of finding new disposal sites when some of the current sites are filled.

The network flow model as developed by the operations research team was reported in the Second Annual Report. Since then the model has been subjected to actual applications, and in the process, some revisions have been made. The revised model and the results of its application to the nine-county San Francisco Bay Area are reported in a later section of this report.

The preceding six objectives have been carefully scrutinized and the substantive progress achieved in varying degrees of completion is given in this report, and was alluded to in earlier progress reports.

The following objectives (objectives 7-10) are discussed only briefly because they are still in the planning stage and will form the subject of future investigations. These objectives represent a continuation of thought and are discussed briefly. The actual plans for their execution depend to a large extent on completing some of the unfinished work reported earlier.

Regional Economic Forecasts of Employment, Income, Population, and Land Use Through Input-Output and Other Related Studies

In the course of developing information for achieving earlier objectives, a vast amount of spatial data on the economy was collected. These data can be used in projecting future waste quantities to be handled within the system. The detailed input-output model for forecasting the regional economy discussed in the First Annual Report [4] will be enlarged to contain as many different economic sectors as possible and at the same time be consistent with the waste generation model. Such an expansion will facilitate the projection of the regional economy and the utilization of the waste multipliers which were estimated earlier, for the development of the necessary forecasts of waste generation.

Although it is proposed to develop forecasts of the regional economy and the waste quantities within the model, it will nevertheless be necessary to obtain forecasts of income, land use, and other allied forecasts from outside the model. The latter pieces of information will be obtained from ongoing outside economic studies of land use and population changes, for example, the Bay Area Simulation Studies carried out by the University of California at Berkeley.

Technical Changes in Existing Methods and Consideration of New Methods of Transfer and Disposal for Future Management of Solid Wastes

The development of the necessary research procedures for achieving this objective depends to a large extent initially on the fulfillment of specific objective No. 4 viz., "Survey of existing methods of transfer and disposal," and of specific objective No. 5 viz., "Analysis of expenditure by functions." The additional changes brought about by technological advances in the engineering methods of transfer and disposal will be appraised fully, along with their implications on the cost structure and management issues. The end result of this objective will be the provision of realistic, economic, and meaningful alternatives of combinations of various engineering methods for incorporation in the formulation of proposals for optimization purposes.

A Systems Analysis Approach to Solid Wastes Management

This penultimate objective involves various aspects, among which are: a) the development of comprehensive procedures to take into account the enormous detailed information developed in the research done thus far; b) the recognition of the need for spelling out in detail the subsystems of the overall management program; c) the detailed listing of all feasible alternative combinations of engineering processes; d) an estimation of corresponding direct and indirect costs; and e) a study of the implications of different combinations of all feasible solutions. This item of work will be pursued vigorously in the future, but the initial setting up of the various subsystems and the various mathematical models developed in the study thus far is expected to be completed during the year 1970-71.

Implementation of Proposed Regional Solution, Recognizing the Changes Caused by Increasing Demand for an Overall Solid Wastes Management Program, Jurisdictional Conflict, Efficiency and Equity Criteria Stemming from Different Pricing Mechanisms, and, Finally, Horizontal Integration with Other Similar Urban Services Under a Regional or Metropolitan Government

This ultimate objective is manifold, having several minor objectives each with its own practical ramifications during its implementation. The detailed nature of the work involved in achieving this essential objective will depend to a large extent upon the wealth of information developed in the overall research program. Especially important aspects of the management problem are the administrative and sociological (or political), inasmuch as together they constitute the sine qua non so far as the implementation of any regional approach to management is concerned.

The following items are listed as guidelines for developing the necessary details for achieving this final objective:

1. A description of the regional economic profile and the waste generation process.
2. Local vs. regional solution economies of scale of operations.
3. Jurisdictional questions in estimating the total quantity of demand and supply of the waste management industry.
4. Efficiency, equity and externalities, incidence and distribution of costs and benefits.
5. Private vs. public or semipublic participation in the waste management industry.
6. Alternative pricing mechanisms to bring about desired distribution and incidence of costs and benefits, taxation, subsidies, municipal bonds and user charges, need for developing incentives for regional management.
7. Proposal of alternative solutions with full implications and trade off between transport and disposal of solid wastes.
8. Horizontal aggregation with other similar urban services under a regional or metropolitan governing body – merits and demerits.

To recapitulate briefly, the rationale of the Planning and Economics phase of the comprehensive research approach has been that "some fraction of the solid wastes residue must be returned to the earth, at least in the foreseeable future, even if efforts are made to compact, transport, treat, and burn the solid wastes." This has led to the recognition of landfill as the single most important method of disposal — at least for the coming few years. The recognition of landfill as the important disposal method has serious implications for land-use planning, and there is a great need to carry out some feed-back studies between secular land-use planning studies traditionally carried out by private and public planning bodies and the waste management studies, such as those contemplated in this research program.

On a different front, refuse disposal has already been recognized as one of the major items for regional or metropolitan planning, along with other urban services such as air pollution control, regional parks, land transportation, and regional planning in general. This aspect has serious implications from the administrative, regulative, and managerial points of view which in waste management programs may in some instances be horizontally aggregated with other similar urban services, chiefly to reduce unnecessary multiplicity and/or conflicts in governing bodies.

The interrelatedness of solid waste disposal and other urban services at the local and regional levels makes it imperative that the final analysis of the implementation phase of the solid waste program effectively progress, and in turn contribute to the overall process of planning for public services.

ECONOMIC AND PLANNING ASPECTS OF TECHNOLOGY

Until quite recently, the disposal of solid wastes was for the most part carried out in a somewhat haphazard fashion, with very little attention given to planning beyond immediate needs. Cities generally had little difficulty in finding new and convenient disposal sites, and so could afford to postpone planning until the existing dump capacity was nearly exhausted. However, with the enormous rise in waste generation during the past twenty-five years and the increasing scarcity of open land within cities, random disposal has of necessity been replaced by attempts at planning for future disposal needs.

Along with planning in the prevention of environmental pollution comes the question of which method or methods of disposal is most effective in terms of cost per ton of waste disposed of, and at what point any given technology will cease to be as efficient as some alternative. To gain some information on these questions a survey was made of conventional and of experimental methods of solid waste disposal, and an analysis was made on the economic practicability of each in terms of present and future needs and scarcities. For example, the study considered what parameters might cause incineration or any other method to become more efficient than landfill. Included in conventional technology are the disposal methods landfill, incineration, and composting. Among the techniques which may be classified as experimental are compaction at the disposal site, wet oxidation, anaerobic digestion, and biological fractionation. In the discussion to follow, each of the foregoing methods is discussed in terms of the process and equipment required, possible by-products, and costs.

An idea of the nature of the material to be processed by a given disposal method can be gained from a perusal of Tables 1 and 2. Apparently, approximately 64% of the wastes is rubbish, 12% food preparation residue (garbage), and 24% noncombustibles. In terms of the elemental composition that is expected of municipal refuse, about 28% may be carbon; 3.5%, total hydrogen; available hydrogen, 0.7%; oxygen, 22%; nitrogen, 0.33%; and sulfur, 0.16%. Such a mixture would be about 4,917 Btu/lb.

TABLE 1

COMPOSITION AND ANALYSIS OF AN AVERAGE MUNICIPAL REFUSE[a]

Item	Total Refuse %	Approximate Analysis[b] "As Received" Basis, Weight %				Ultimate Analysis, Dry Basis, Weight %							Btu per lb		
		Moisture	Volatile Matter	Fixed Carbon	Non-Comb.[c]	Carbon	Total Hydrogen	Available Hydrogen	Oxygen	Nitrogen	Sulfur	Non-Comb.[c]	Ratio C:(H)	Dry Basis	Dry, Ash-Free Basis
Rubbish, 64%															
Paper, Mixed	42.0	10.24	75.94	8.44	5.38	43.41	5.82	(0.28)	44.32	0.25	0.20	6.00	155	7,572	8,055
Wood and Bark	2.4	20.00	67.89	11.31	0.80	50.46	5.97	(0.672)	42.37	0.15	0.05	1.00	75	8,613	8,700
Grass	4.0	65.00	--	--	2.37	43.33	6.04	(0.83)	41.68	2.15	0.05	6.75	52	7,693	8,250
Brush	1.5	40.00	--	--	5.00	42.52	5.90	(0.75)	41.20	2.00	0.05	8.33	56.7	7,900	8,600
Greens	1.5	62.00	26.74	6.32	4.94	40.31	5.64	(0.77)	39.00	2.00	0.05	13.00	52.4	7,077	8,135
Leaves, Ripe	5.0	50.00	--	--	4.10	40.50	5.95	(0.31)	45.10	0.20	0.05	8.20	131	7,069	7,700
Leather	0.3	10.00	68.46	12.44	9.10	60.00	8.00	(6.56)	11.50	10.00	0.40	10.10	9.1	8,850	9,850
Rubber	0.6	1.20	83.98	4.94	9.88	77.65	10.35	(10.35)	--	--	2.0	10.00	7.5	11,330	12,600
Plastics	0.7	2.00	--	--	10.00	60.00	7.20	(4.40)	22.60	--	--	10.20	13.6	14,368	16,000
Oils, Paints	0.8	0.00	--	--	16.30	66.85	9.65	(9.00)	5.20	2.00	--	16.30	7.43	13,400	16,000
Linoleum	0.1	2.10	64.50	6.60	26.80	48.06	5.34	(3.00)	18.70	0.10	0.40	27.40	16	8,310	11,450
Rags	0.6	10.00	84.34	3.46	2.20	55.00	6.60	(2.70)	31.20	4.62	0.13	2.45	20.4	7,652	7,844
Sweepings, Street	3.0	20.00	54.00	6.00	20.00	34.70	4.76	(0.36)	35.20	0.14	0.20	25.00	96	6,000	8,000
Dirt, Household	1.0	3.20	20.54	6.26	70.00	20.62	2.57	(2.07)	4.00	0.50	0.01	72.30	10	3,790	13,650
Unclassified	0.5	4.00	--	--	60.00	16.60	2.45	(0.166)	18.35	0.05	0.05	62.50	100	3,000	8,000
Food Wastes, 12%															
Garbage	10.0	72.00	20.26	3.26	4.48	44.99	6.43	(2.845)	28.76	3.30	0.52	16.00	15.8	8,484	10,100
Fats	2.0	0.00	--	--	0.00	76.70	12.10	(10.70)	11.20	0.0	0.0	0.0	7.2	16,700	16,700
Noncombustibles, 24%															
Metallics	8.0	3.00	0.5	0.5	96.0	0.76	0.04	(0.02)	0.2	--	--	99.0	51	124	12,000
Glass and Ceramics	6.0	2.00	0.4	0.4	97.2	0.56	0.03	(0.02)	0.11	--	--	99.3	34	65	8,000
Ashes	10.0	10.00	2.68	24.12	63.2	28.0	0.5	(0.40)	0.8	--	0.5	70.2	70	4,172	14,000
	100.0														

[a] Source: Bell, John M. "Characteristics of Municipal Refuse," National Conference on Solid Waste Research Proceedings, December 1963.

[b] Based on ASTM methods of analysis of coal and coke, as adapted for refuse.

[c] Noncombustibles — ash, metal, glass, and ceramics.

TABLE 2

ANALYSIS OF COMPOSITE REFUSE

Organic Analysis of Composite Refuse

Item	Percent
Moisture	20.73
Cellulose, sugar, starch	46.63
Lipids (fats, oils, waxes)	4.50
Protein, 6.25N	2.06
Other organic (plastics)	1.15
Ash, metal, glass, etc.	24.93
	100.00

Analysis of Composite Refuse, as Received Basis

Moisture	20.73
Carbon	28.00
Total Hydrogen	3.50
Available Hydrogen	(0.71)
Oxygen	22.35
Nitrogen	0.33
Sulfur	0.16
Non-Comb.	24.93
Ratio C:(H)	39.4
Btu per lb	4917

Summary Description of Features of Conventional Technologies Pertinent to Economic Analyses

Landfill. By far the most common method of waste disposal at present is some form of landfill. Three dimensions can be distinguished in classifying fill operations. First, a site may be called a sanitary landfill, modified landfill, or open dump, according to whether the garbage is covered with soil at the end of each day, covered periodically, or not covered at all. Second, a dump may be classed as controlled or uncontrolled. It is controlled if the manner of dumping, area of the site to be used, and/or the type of refuse accepted is carefully designated. Finally, the landfill technique may be a trench fill or an area fill.

Trench and area landfills are somewhat similar - the major distinction being preparation of the earth before dumping. The area method involves construction of cells of refuse covered by compacted earth on flat or low-lying open spaces. Since no excavation is undertaken, cover material must be imported from outside the landfill itself. The trench method entails excavation of trenches several yards wide followed by the discharge of solid wastes into the trench. Both methods include the dumping and compaction of garbage anywhere from 25% to 40% of its original volume; and for a sanitary landfill, covering the refuse with two feet of earth (ideally). The refuse usually is compacted in layers, or lifts, five to fifteen feet deep, creating a cell-like effect. Total depth of landfills vary widely, depending upon the number of lifts [5]. Compaction is accomplished by the movement of earth movers, bulldozers, and like equipment over the refuse. In Table 3 is summarized the equipment used in typical trench and area fill operations.

In practice deep-hole landfill should be used with caution because of the danger of water contamination connected with its use. The method is to excavate a pit to a depth of fifty feet or more; or if one is at hand, to use an abandoned quarry or open pit mine, and to fill the hole with compacted solid waste and earth. With any landfill method, climatic, hydrologic, and geologic factors of an area determine how deep a lift may be without danger of contamination. Few locations can safely accept a deep-hole landfill, though the method is used in parts of the south and several sites in California [5].

Canyon or gully landfill incorporates the most desirable elements of both area and trench fill methods. A canyon is filled with cells of refuse in much the same way as an area fill. However, cover material may be scraped from the canyon sites to avoid the cost of importing earth. A canyon fill results in relatively level ground, while a trench fill raises the surface five to ten feet above the original ground level [5].

The method of fill best suited to any operation is largely dependent on the charecteristics of fill land. Tidelands, marshes, and swamps, and other reclaimable lands are amenable to area fill. In the absences of such areas, trench, canyon, or deep-hole fill must be used, depending on the terrain.

Incineration. Incineration of solid waste by modern techniques is a fairly complex combination of subprocesses [6]. Collection trucks generally enter an enclosed area (called a tipping floor) and discharge their contents into a deep, box-like storage pit of watertight concrete construction. Capacity of the pits vary. They should hold an amount approximately equal to a twenty-four hour burning capacity. Usually, refuse is carried from the storage pit to the furnace by a bridge-type or monorail crane suspended from an I-beam and is discharged into a hopper leading to the furnace.

Actual incineration of the waste takes place in furnaces lined with refractory and insulated brick designed to withstand extremely high temperatures and equipped with agitating metal grates. The residue of ashes, cans, and other nonburnables is discharged into hoppers, quenched, and conveyed by truck to disposal sites, usually landfills. This residue varies from ten to twenty percent of the original volume, and twenty to thirty-five percent of the original weight [6].

TABLE 3

LIST OF EQUIPMENT REQUIRED FOR LANDFILL

Method	Equipment
I. Area Method This method is best suited to filling in low-lying areas such as tidelands, marshes, and swamps. The basic operations for which equipment must be provided includes: A. Unloading fixed bed trucks. B. Spreading and compacting refuse. C. Obtaining and stockpiling cover material. D. Placing and compacting cover on refuse fill. E. Final grading of finished landfill.	A "single crawler-type tractor" equipped with a dozer blade (bulldozer) or a bullclam attachment may perform all these operations. For larger operations: 1. Bulldozer. 2. Compacting equipment. 3. Water trucks. 4. Earth movers. (Note: APWA's publication on municipal refuse disposal suggests one bulldozer of the 180 drawbar h.p. class and 4700 lb gross wt size to handle about 250 tons of refuse per day.)
II. Trench Method The trench method is most often employed where flat or gently sloping areas are available. It is adapted to use on terrain which can be trenched by normal earth-moving equipment.	A single belt-propelled crawler crane with a drag bucket and a boom serves satisfactorily for all the operations.

Exhaust gases given off by the combustion of the waste flow to the combustion chamber, which may be simply an extension of the furnace, where the gases are burned along with any suspended particulate matter at 1800°F. Gases then flow to the subsidence chamber where the destruction of noxious gas and fine particulate matter is completed, and any remaining particles are settled out to reduce pollution of the atmosphere. Finally, chimneys conduct the burned gases to the atmosphere about 150 to 200 feet above ground level. In Table 4 is listed the required equipment for each stage of the process.

Several types of pollution control devices can be included in the subsidence chamber and/or the chimney. The simplest of pollution control devices use water to collect ash and dust particles either by moistening a system of baffles through which the gas must pass, or by using a spray to capture and remove the particles

TABLE 4

LIST OF EQUIPMENT FOR CONTINUOUS INCINERATION

Process	Equipment
1) Receiving of refuse.	a) Storage pit.
2) Charging the incinerator furnace.	a) Bridge crane.
	b) Grab bucket.
	c) Charging hopper with hopper gate.
	d) Feeding and drying stoker.
	e) Burning stoker.
3) Incineration.	a) Primary combustion chambers.
	b) Secondary combustion chambers.
4) Release of gases and ash.	a) Gas cleaning chamber.
	b) Flue.
	c) Damper.
	d) Chimney.
	e) Ash hoppers.
	f) Ash conveyors.
5) Instruments and controls.	a) Indicating and recording pyrometers for temperature measurement.
	b) Temperature alarms.
	c) Draft gages at several points in the system.
	d) Smoke meters and alarms.
	e) Automatic gas-cooling water controls.
	f) CO_2 recorders.
	g) Continuous chimney dust indicators.

(e.g., "wet scrubber"). A wet scrubber removes dust particles by causing impinging dust particles to be projected into a thoroughly dispersed scrubbing liquid. Additionally, a spray chamber may be used to cool gases and moisten particles prior to their removal by cyclone collectors. The latter device is a cone-shaped cylinder in which entering gases are forced into a spiraling, cyclone-like motion. The resulting centrifugal force directs particles to the outer wall of the collector while the core of clean air is drawn out through the bottom. The difficulty with wet baffles, wet scrubbers, and cyclone techniques is their limited efficiency. Though these are virtually the only pollution control devices used with incinerators in the United States today, they cannot meet the standards set by the more discriminating large metropolitan areas such as Los Angeles and San Francisco.

Two far more efficient methods of removing particulate matter are the bag filter and the electrostatic precipitator [7]. The former is in effect a reverse-flow fiberglass unit mounted on a spider framework. It works somewhat like the bag filter in a vacuum cleaner. One problem with this filter is that excessive heat or air pressure will cause it to fail. Therefore, it is necessary to cool exhaust gas in a spray chamber or water-cooled furnace and to bring about a pressure drop in the flow of gas. This is a fairly expensive but very effective procedure. The electrostatic precipitator [8] consists of small-diameter discharge wires and collecting plates or tubes between which the gas and particles must pass. Particles passing through the precipitator are given a charge and thereby precipitated against poles of opposite polarity in the precipitator. The particles are then discharged and removed from the wires and collecting surfaces. The precipitator, like the bag filter, cannot function at high temperatures and high air pressure. Consequently, it too requires some sort of cooling system, (e.g., a spray chamber or water-cooled furnace) and a pressure drop.

Composting. Composting can be described as a process in which aerobic bacteria break down organic wastes to a relatively stable, inoffensive humus under controlled conditions. The required bacteria are indigenous to garbage, so that the process requires only that garbage be ground and suitably aerated, as well as be maintained at a proper moisture content. A compost of garbage and other refuse can be considered finished when the carbon-nitrogen ratio is below 20:1. At that ratio, it may be safely used as a soil conditioner. The required time to complete the process is from 8 to 30 days depending upon the nature of the wastes and the method used. Major factors in the composting process are particle size and moisture content of the material, aeration, temperature, hydrogen-ion concentration, and the initial carbon-nitrogen ratio. The smaller the particle, the more susceptible it is to bacterial action because of the greater surface exposed per unit of volume. Moisture content affects the metabolism of the organisms and changes the physical structure of the material. Aeration provides oxygen, which is essential for aerobic bacteria in carrying on the stabilization process. Microorganisms are sensitive to temperature changes and generally metabolize more rapidly at the higher temperatures within the range in which they will grow. Generally, bacteria thrive best at moderate to low hydrogen-ion concentration (alkaline) and fungi at moderate to high concentrations (acid). Carbon serves as an energy source, and nitrogen for use in building protoplasm.

Composting is, of course, only suitable for certain types of waste matter. Of the remaining the main noncompostables in municipal refuse are bottles and broken glass, 11.7%; and tin cans, 9.8%. As for the chemical composition, the average C:N ratio of refuse ranges from 78 to 20. The concentration of fertilizer elements are rather low, namely, nitrogen, 1.07%; phosphorus as P_2O_5, 1.16%; and potassium as K_2O, 0.83%. Moisture content varies from 25% to 70%. It averages about 50%. These characteristics are reflected in the compost product.

Two classes of composting may be distinguished as being possibly economical and certainly adaptable to conditions in the United States. They are mechanical digestion and modified windrowing. Both techniques involve the need for facilities for storing and separating solid wastes into compostables and noncompostables, as well as for grinding or shredding the garbage. In the separation step, noncompostable materials, such as tin cans, miscellaneous metals, glass and ceramic ware, and rags are removed from the incoming refuse. Grinding or shredding reduces the particle size to a point at which the material is readily susceptible to bacterial attack. The optimum particle size depends on the nature of the material. Generally, it is from 0.5 in. to 2 in. in cross-section.

Mechanical digestion involves the use of enclosed devices of varying degrees of complexity. The devices include provisions for maintaining the composting mass at a suitable moisture content, temperature, and degree of aeration. No such mechanical devices are used in windrow composting. Instead, the shredded material is stacked in windrows in the open. Periodically, the material is turned to aerate it. A typical list of equipment is given in Table 5.

End Products of Conventional Disposal Methods

Each of the conventional waste disposal methods leaves some residue or produces some product. Though the existence of such products or residues may not affect the physical or technical efficiency of a process, it certainly affects the economic efficiency and social desirability of the process. Since any discussion of disposal costs must include implicit costs, positive or negative, a careful enumeration of the by-products of each existing technique is indicated at this time.

Sanitary Landfill. Any sanitary landfill operation will result in a certain amount of usable land after completion. If the operation involves filling a swamp, bay, or quarry, the end product will probably be a net addition to usable land. If useful land is filled, the result may only be some small degree of land improvement. In evaluating the degree of land improvement, it should be borne in mind that the property so treated has very little utility upon completion of the filling operation. Its main use is as open space or for recreation, since the land will continue to settle for years and methane gas will be generated in the completed fill for some time. Both of these effects would be detrimental to any major construction. The danger from the methane generation is that the gas (highly explosive when mixed with air) may seep into the understructure of buildings constructed on the site, and thus give rise to an explosive hazard.

Methane is not the only gaseous product in a landfill; carbon dioxide also is formed. When dissolved in water, the resulting carbonic acid can be corrosive, and it also deteriorates the quality of groundwater permeated by it. Leachates containing biological and chemical contaminants constitute another type of product which must receive attention. Odor generation, leachate formation, and water contamination in general can be eliminated through the application of the sanitary landfill method in its strictest application. Settling can be lessened through rigorous compaction. Not much can be done about methane formation.

Needless to state, open dumping has no place in modern waste management practice. In addition to being a blatant affront to even rudimentary aesthetics, it has the additional disadvantage of producing a public health hazard and destroying the land it occupies. The cost of potential disease emanating from such sites is difficult to measure, but would certainly constitute an important negative element.

Incineration. End products most commonly associated with incineration are ash and the gaseous and particulate discharges which constitute air pollution. The damage resulting from such air pollution is too well known to warrant much further discussion in this report. The extent of air pollution is a function of incineration design, operating procedure, completeness of combustion, and the refuse being fired. Given sophisticated control devices such as the electrostatic precipitator, incineration need not cause any appreciable pollution by present standards. Toxic gases and odors cannot presently be eliminated from incinerator exhaust, but may be reduced by restricting the type of refuse to be burned, or by scrubbing devices yet to be prefected.

Inert ash and nonburnable objects constitute additional end products of incineration. Depending upon the efficiency of the incinerator, the volume and weight of the ash should be from 10% to 30% of those of the incoming refuse. Tin cans and metallic objects make up the greater part of the noncombustibles.

TABLE 5

LIST OF EQUIPMENT REQUIRED FOR COMPOSTING

Process	Equipment
Mechanical Method:[a]	
1) Segregation of refuse, magnetic and hand separation process.	a) Magnetic separator to remove ferrous material. b) Suction blower to remove paper.[b] c) Conveyor belts.
2) Grinding.	a) Primary grinder. b) Secondary grinder. c) Final grinder.
3) Mixing with sewage sludge.[c]	a) Sewage sludge tank.[c]
4) Digestion process.	a) Enclosed digester. b) Air heater.
5) Finishing process.	a) Dryer.[d]
Windrow Method:[e]	
1) Receiving of refuse.	a) Hopper.
2) Segregation of refuse: Magnetic and hand separation process.	a) Magnetic separator.
3) Grinding of the refuse: Rough grinding.	a) Rasping machine, hammermill, or other type of grinder.
4) Glass and metal separation.	a) Ballistic separator.[c]
5) Composting.	

[a] The equipment used by Metro Plant in Houston, Texas.

[b] Optional.

[c] Sewage sludge is used.

[d] In Metro Composter only.

[e] The equipment used by the Tel Aviv Plant.

A somewhat less important characteristic of incineration is the necessity of a smokestack, which breaks up the skyline and mars the little beauty that still exists in modern cities. A better cleaning of exhaust should permit a reduction in the required height of an incinerator stack.

On the more positive side, incineration generates a great amount of heat which can be coupled with a cooling device to generate steam. If properly designed and some provision is made to contend with the traffic of refuse collection trucks converging at the site, an incinerator could be located fairly close to the point of waste generation. If this could be done, obviously transport costs would be reduced. The sale of the heat-steam product would necessitate a location near the market for the steam. One possible disadvangage along these same lines is the reluctance of the city resident to accept an incinerator in his neighborhood. If opposition is very strong because of a popular and often true conception of an incinerator as a smoke-belching monster, the facility may have to be located as far outside of populated areas as would a landfill operation, and thereby eliminate the potential advantage of reduction in transport costs.

Since solid waste is not completely destroyed by incineration, the principal positive product of this process may be thought of in terms of reduced landfill requirements. Thus, if an incinerator reduces the compacted volume of wastes by 80%, the useful life of a landfill is extended correspondingly. Since incineration reduces the amount of land required for waste disposal, land costs probably will be one of the determinants in ascertaining whether or not incineration (or any other process) is desirable.

Composting. At one time it was believed that compost would prove to be a positively, or at least nonnegatively valued product, if not for its properties as a fertilizer, which are minor, at least for its soil-conditioning qualities. A typical compost made from municipal refuse will have on a dry weight basis from 0.5% to 1.5% nitrogen, 0.75% to 1.5% phosphorus, and from 0.5% to 1% potash, in addition to valuable trace elements required by growing plants. Obviously, the addition of animal manure, sewage sludge, or slaughterhouse wastes to the refuse to be composted will result in an increase in the final fertilizer values of the compost product. Nevertheless, even though additives can enhance the fertilizer value of a municipal compost, its best use will be as a soil conditioner.

At present a large-scale market for the compost product is nonexistent. One reason is that the costs of hauling and spreading compost are prohibitive in comparison with those for synthetic fertilizers; and moreover, most farming areas already have a plethora of readily available soil conditioners in the form of manure and plant trimmings which they are paying to have hauled away [9]. In fact, unless some great difficulty arises with other disposal methods, composting cannot be considered a viable alternative. The end product can rarely even be given away, and since the volume is reduced by only 33% at most, no large proportion of land is saved by its use.

A modified form of composting, termed low-cost biostabilization [1], has been suggested as a possible means to circumvent the absence of a market for compost. In this process the actual composting operation is kept to a minimum, i.e., only enough to keep the processed refuse from posing an affront to the environment. Another feature is that the land is "loaded," not in terms of soil amendment, but solely in terms of acceptance up to (but not including) that level at which point the land would be permanently damaged. Unlike landfill, the capacity to absorb waste is never completely exhausted. Low-cost biostabilization probably still belongs in the experimental class and is discussed in this section only because it is closely related to the composting process.

Comparative Costs of Conventional Disposal Methods

For all practical purposes—at least at the time of this writing—incineration and some form of landfill seem to be the only feasible methods of waste disposal. It should be possible, given the disposal process and by-products of the two techniques, to form some basis upon which to compare costs to determine which is more efficient in terms of economy.

Landfill. The determination of land cost in a landfill operation presents some quite complex economic questions. Theoretically, the cost of land should be the initial cost less the discounted value of land sales to be realized at some future date. This total cost can then be apportioned to find an annual rental figure. The future date in this case is from 15 to 20 years, i.e., the time needed for land to completely settle and waste matter to decay after the filling is completed. In the interim, however, the land may be used for open space, parks, or other recreational purposes. If the latter are necessary facilities which would have been provided in the absence of landfill, the rental value of alternative open spaces should be included as part of the gain to the providing government, analogous to sales revenue.

Another question is whether or not a pure rent should be included in the calculations. Suppose, for example, that government takes a prime piece of land in the center of the city, which will certainly appreciate in value at a rate of 10% a year, and uses it for landfill. Suppose, further, that the appropriate rate of discount for public endeavors is 9% per year. At the end of twenty years, the original calculations would show land cost to have been negative. Would this be an accurate measure of the cost to the economy of using the piece of land for waste disposal? It probably would not. After all, the interest is not in the accounting balances of a municipality or region, but in the real effect upon resource use. For a certain period of time, land was unavailable for alternative productive uses, and this constitutes the real cost to the economy of the community in question. It only appears to be a negative cost because of a pecuniary (not real) change in land value. Thus, the possibility of rental values. (The point is whether an increase in the rent earned by land should be considered to offset the real cost of land use.)

Finally, how does one treat the value of land for which no market price exists? Such is the case with reclaimed land or municipally owned land with no direct rental charge levied for use as a disposal site. Possibly some rental value can be imputed from surrounding properties for which a market does exist.

If some acceptable method of evaluating rental costs could be formulated, it would be fairly simple to form a cost function per ton of waste for landfill. Costs, other than those for land, currently amount to from under fifty cents per ton to over three dollars, depending on the site surveyed. It should be possible to use a regression technique to find a total or average cost function for landfill in general.

Another distinction between local and remote disposal site may be a different quality of landfill operation. Open dumping at the distant site may reduce explicit costs, but it simultaneously leads to deterioration of the countryside, or to the building up of a health menace in the future. This sort of cost is likely to be completely external to the city doing the dumping. It is analogous to a public good in that it is a consequence of many cities' dumping, so that one city more or less would make very little difference.

Incineration. Excluding adequate pollution control devices, the explicit costs of incineration ran from about four dollars to over twelve dollars per ton. Adequate air pollution control features would add more than $2.00 per ton in the case where no control apparatus is used, and could increase the cost by a minimum of $1.20 per ton where baffles or cyclone collectors are already installed. As with landfill, it should be possible to regress cost per ton incinerated on several important variables such as air pollution equipment, age of the equipment, and how close the operation level is to capacity.

Until the mid-1960's, relatively little attention was given in the United States to the possibility of selling the heat and potential steam by-products of incineration. It has been suggested that the steam might be used to heat city buildings, be sold commercially, or used to generate electricity. Whether or not reclamation of the heat energy released in incineration would be econimically feasible depends upon the heating value of solid wastes, the cost of alternative fuels in the relevant area, the additional construction, operation, and maintenance costs incurred by using refuse as fuel, and the cost of alternative disposal methods. Access roads for trucks, scales, buildings, and equipment for storing and loading refuse into the furnaces, and residue disposal facilities will all act to raise capital, operation, and maintenance costs.

The sale of these products could be carried out either directly by the local government or through the leasing of facilities for electrical generation to private companies [10].

Composting. Composting has never reached a stage in the United States at which much data on cost of composting as a process could be obtained. During its brief operation, the demonstration plant at Gainesville, Florida, ran at a cost of $6.25 per ton of waste processed. This figure probably is conservative and gives no idea of what could be expected from plants of larger size. Although low-cost biostabilization might at first sight seem a more acceptable method than conventional composting, experimental results thus far indicate that as a technology, it needs considerably further research before it can be accepted as a feasible waste-processing method. Preliminary figures indicate that for a city of 100,000, low-cost biostabilization might entail an expenditure of from $7 to $8.50 per ton of waste processed, depending on the quality of compost. This cost figure undoubtedly is somewhat higher than what the actual costs would be. However, it does indicate a rather high disposal cost, even were no residue to remain when the process was completed. It would seem, then, that neither the conventional composting nor the low-cost biostabilization processes would be likely choices for disposal technique in this country in the near future, or at least in areas where either landfill or incineration are feasible.

A Study of Variations in Landfill Costs

The complexities arising from the various factors influencing economics of scale in landfill let to the present study of variations in landfill costs. Currently, landfill is the most commonly used method of disposal. Reported costs of landfill range from about $0.50 per ton for facilities operated in a haphazard manner to some $2.00 per ton for those which qualify as true sanitary landfills. According to Black et al.[11] and to Cannella [10], the average cost for sanitary landfill is about $1.13 per ton.

The purpose of this particular study was to develop a cost function for landfill from empirical data that would make it possible to identify those parameters which most directly affect costs. Such a cost function makes it possible to analyze the efficiency of existing site operations and might lead to the formulation of suggestions and cost estimates that will improve existing and future operations.

Theoretical Background. Much of the theoretical background needed for the study is contained in the general economic theory which assumes that at any point in time, output of any product bears a certain relationship to inputs in the production process. The most general form of the production function is given by

$$Y = f(x_1, x_2, \ldots, x_n)$$

where Y represents output, and x_i represents inputs to the production process. The functional form "f" can be estimated by minimizing the cost of production for any level of output in a certain range of output. Cost, of course, is given by the summation of products of prices and quantity of inputs as in C:

$$C = P_1x_1 + P_2x_2 + \ldots + P_nx_n$$

where C is total cost and P_i is the price of one unit of input i.

It is possible to formulate a Lagrangian equation in order to derive first-order conditions for cost minimization, given some level of production.

Minimize C, where

$$C = P_1x_1 + P_2x_2 + \ldots + P_nx_n - \lambda\,[f(x_1, x_2, \ldots, x_n) - Y]$$

$$1)\ \frac{\delta C}{\delta x_1} = P_1 - \lambda\frac{\delta f_1}{\delta x_1} = 0 \quad\text{or}\quad P_1 = \lambda\frac{\delta f}{\delta x_1}$$

$$2)\ \frac{\delta C}{\delta x_2} = P_2 - \lambda\frac{\delta f}{\delta x_2} = 0 \quad\text{or}\quad P_2 = \lambda\frac{\delta f}{\delta x_2}$$

$$\vdots$$

$$n)\ \frac{\delta C}{\delta x_n} = P_n - \lambda\frac{\delta f}{\delta x_n} = 0 \quad\text{or}\quad P_n = \lambda\frac{\delta f}{\delta x_n}$$

$$n+1\ \frac{\delta C}{\delta \lambda} = -\,f(x\quad x_2,\ldots,x_n) + Y = 0 \quad\text{or}\quad Y = f(x_1,x_2,\ldots,x_n)\ .$$

Thus, a system of n+1 equations in n+1 unknowns is developed. Substituting the first n equation into the last equation leads to the solution for input demand in terms of prices and output. That is,

$$x_1 = g_1(Y,\ P_1,P_2,\ldots,\ P_n)$$

$$x_2 = g_2(Y,\ P_1,P_2,\ldots,\ P_n)$$

$$\vdots$$

$$x_n = g_n(Y,\ P_1,\ P_2,\ldots,\ P_n)$$

Substituting into the original cost equation for x_i

$$C = P_1 \cdot g_1(Y,P_1,\ldots,\ P_n) + P_2 \cdot g_2(Y,P_1,\ldots,\ P_n) + \ldots + P_n \cdot g_n(Y,P_1,\ldots,\ P_n)$$

$$\therefore\ C = c(Y,\ P_1,P_2,\ldots,\ P_n)\ .$$

This analysis raises some questions concerning the relevant inputs for the production function of landfill. Obviously, the process will use some amounts of labor, land, and capital equipment both in the actual disposal operations and in their administration. In addition, one would expect the use of capital improvements on land such as fencing, diking, roads, structures, and cover material.

These inputs are not homogeneous in character. Labor, for example, may be broken into sub-classes, e.g., clerical, supervisory, and operational or technical. Technical labor, which actually performs the physical task of disposal may be differentiated by levels of skill. That is, labor skill is likely to range from highly paid heavy-equipment operators to manual laborers. Similarly, though equipment is nominally fairly uniform, some important variations may exist in size and quality. A site usually will involve the use of some combination of bulldozers, graders, trucks, and cranes. Furthermore, a classification such as "trucks" or "bulldozers" may be differentiated in two dimensions according to horsepower and capacity. There is no set proportion in which equipment must be used. The nonhomogeneity of inputs and output is a problem that is always encountered in economic analysis. A trade-off exists between operational usefulness and a completely specified theoretical model. The function of a model, in this case either a production function or its concomitant cost function, is to succinctly enumerate the most important elements of a process. Only then can the results of a change in process be seen, and analysis and planning be possible. It may not be desirable to enumerate all sources of cost variation. What is needed are the most significant sources and some indication of their qualitative and quantitative impact. The level of aggregation of variable-labor, capital, or land, and the details obscured by such aggregation becomes a matter of the researcher's judgment—given the data available and the purpose of the model.

The most important variables in a general landfill cost function are expected to be labor, land rental, and capital equipment. In addition, some qualitative variables are expected to be important, e.g., lift depth, age of site, site location, sanitary conditions at the site, and site capital improvements.

The technique utilized to determine the sources of cost variation in landfill is regression analysis. Given data on a site's total and average costs, certain elements of those costs and other variables (chosen to indicate qualitative characteristics) are regressed against total and average costs. The positive or negative sign and the magnitude of each regression coefficient (in relation to its standard deviation) will indicate those variables which most significantly influence costs.

Empirical Study. The data presented in Table 6 were gathered in 1968-69 by questionnaire. Only the data about which there is a reasonable level of accuracy are reported. Land is conspicuously absent. Although some data on land exist; they require further refinement. Work is in progress on this and during the coming year it should be possible to incorporate land rents into the model. Until then it has been excluded from all calculations. Column 12 (Site Modifications) in the table includes the capital costs necessary before raw land is ready to receive solid wastes. In some cases this will consist of roads, fences, diking, and scales; in others only one or two of these improvements may have to be made. This type of investment is essentially "lumpy" and fixed in nature. If the site already is prepared, that fact may be reflected in higher land values. On the other hand, if modification is yet to be done, land thereby may be less expensive. The manner of dealing with costs of site modification must wait until land cost data are in workable form. At that time several approaches will be possible, namely, the cost of land and its modification can be treated as a single fixed cost and amortized over the expected life of the site, or each may be treated separately.

The data on total wages, short-term depreciation, and equipment maintenance and operating costs are complete for 31 sites. Similarly the annual tonnage treated at those sites is known. Data on the number of lifts and their depth are incomplete, thus reducing the sample size to 27 when those qualitative variables are used in the regressions. Work on the data array continues, as previously indicated, and will be reported as they become available.

When the data become available, there will be two basic equations, total cost and average cost, both to be run in linear and log-linear form to make a total of four equations. The nine independent variables will be run in a stepwise regression; i.e., all nine will be present in the first running, and they will be eliminated as their explanatory significance dictates. Complete specification of the model follows:

Independent Variables

Y = tons per year received at each site;

X_1 = lift depth, i.e., number of feet deep each layer of refuse is before it is covered;

X_2 = total annual wages paid;

X_3 = annual ammortized long-term capital, i.e., site modification;

TABLE 6

SUMMARY OF DATA ON LANDFILL COSTS (OBTAINED FROM SURVEY QUESTIONNAIRES)

No. of Observations	Location of Disposal Site		Yearly Waste (tons)	Lift Depth (ft)	Total Wages	Long Term Cap. Expd. (Site Modif.)	Short Term Cap. Expd. (Equip. Depr.)	Maintenance & Equip. Oper. Costs[a]	Sanitary	Site Location
	Name	County								
1	Palos Verdes	Los Angeles	1,330,000		$ 239,452	$ 190,000	$ 138,424	$ 200,659	Yes	Rural
2	Spadra	Los Angeles	142,500		64,957	75,000	24,458	48,192	Yes	Urban
3	Mission Canyon	Los Angeles	1,110,000		225,699	98,000	162,390	472,085	Yes	Urban
4	School Canyon	Los Angeles	450,000		146,942	545,000	79,209	171,709	Yes	Rural
5	Calabasas	Los Angeles	240,000		80,488	104,500	40,105	74,817	Yes	Urban
6	Cannery St.	Orange	139,000	40	17,527	6,034	1,161	12,200	No/Other	Rural
7	Coyote Canyon	Orange	1,020,000	60	178,037	263,027	173,035	148,305	Yes	Rural
8	Olinda	Orange	524,000	60	150,871	163,735	26,670	125,735	Yes	Rural
9	Forster Canyon	Orange	111,000	30	36,744	34,086	22,266	26,584	Yes	Rural
10	Santiago Canyon	Orange	40,800	50	26,435	118,562	18,333	19,481	Yes	Rural
11	Bishops Canyon	Los Angeles	537,000	10	89,000	35,000	14,000	16,000	Yes	Rural
12	Tajigous	Santa Barbara	135,000	20	44,782	20,691	6,231	6,656	Yes	Urban
13	Sheldon Arleta	Los Angeles	460,000	10	115,000	125,000	43,000	46,000	Yes	Rural
14	Toyon Canyon	Los Angeles	294,000	10	124,000	100,000	34,000	36,000	Yes	Rural
15	Chollas	San Diego	232,600	15	58,682	9,000	33,267	98,956	Yes	Rural
16	Otay	San Diego	155,000	15	62,600	54,594	23,949	33,651	Yes	Rural
17	Miramar	San Diego	229,100	15	65,046	9,000	35,409	109,655	Yes	Rural
18	Arizona	San Diego	81,991	15	22,138	6,000	19,864	36,987	Yes	Rural
19	Santa Maria (Airport)	Santa Barbara	12,300	25	10,195	--	1,083	748	Yes	Urban
20	Jamacha	San Diego	102,000	15	36,800	12,200	12,209	38,091	Yes	Rural
21	Tierra Rejada	Ventura	61,397	11	31,772	25,000	12,734	25,027	No/Other	Urban
22	Wagon Wheel	Ventura	95,691	13	47,374	47,200	14,432	47,917	No/Other	Urban
23	Windsor	Sonoma	63,000	6	15,000	41,000	910	49,430	No/Other	Urban
24	Sonoma	Sonoma	34,100	6	15,000	27,500	875	18,190	No/Other	Urban
25	North Coast	San Diego	68,500	15	58,000	2,700	2,758	40,242	Yes	Urban
26	Sycamore	San Diego	91,700	15	60,600	70,201	8,575	41,127	Yes	Rural
27	Solvang	Santa Barbara	8,800		10,026	--	1,969	3,481	No/Other	Urban
28	San Elijo	San Diego	36,900	15	43,700	97,676	6,621	19,679	Yes	Urban
29	Bonsall	San Diego	31,000	15	47,000	54,100	6,118	20,262	Yes	Rural
30	Poway	San Diego	14,596	15	33,100	2,600	4,066	10,634	Yes	Rural
31	Roblar	Sonoma	14,700	6	15,000	22,000	2,531	37,154	No/Other	Urban
32	Palo Alto Muni.	Santa Clara	30,000	18					No/Other	Rural
33	Mountain View	Santa Clara	32,000						No/Other	Rural
34	Sunnyvale	Santa Clara	76,758	28					No/Other	Rural
35	Morgan Hill	Santa Clara	3,900	4					No/Other	Urban
36	Gilroy	Santa Clara	3,640	5					No/Other	Urban
37	Pacheco Pass	Santa Clara	3,900	10					Yes	Urban
38	Guadalupe	Santa Clara	135,000						Yes	Urban
39	Los Altos	Santa Clara	108,000						No/Other	Rural
40	Santa Clara Muni.	Santa Clara	24,000						No/Other	Rural
41	Newby Island	Santa Clara	156,000						No/Other	Rural

X_4 = short-term capital, i.e., equipment depreciation or rental;

X_5 = equipment maintenance and operating cost;

X_6 = miscellaneous costs;

X_7 = dummy variable, equal to 1 if the site qualifies as a sanitary landfill, equal to 0 if it doesn't;

X_8 = dummy variable, equal to 1 if site is in urban area, equal to 0 if it's in rural area.

Definitions are:

$$\text{Total cost} = TC = \sum_{i=2}^{6} X_i$$

$$\text{Average Cost} = AC = \sum_{i=2}^{6} \frac{X_i}{Y}$$

The regression equations to be run are:

1. $TC = \alpha_1 + a_2Y + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + b_6X_6 + b_7X_7 + b_8X_8$
2. $AC = A_1 + A_2Y + B_1X_1 + B_2X_2 + B_3X_3 + B_4X_4 + B_5X_5 + B_6X_6 + B_7X_7 + B_8X_8$
3. $\ln TC = \alpha_1 + \alpha_2 \ln Y + \beta_1X_1 + \ldots + \beta_8 \ln X_8$
4. $\ln AC = \ln \alpha_1 + \alpha_2 \ln Y + \delta_1X_1 + \ldots + \delta_8 \ln X_8$

Choice of Conventional Method

The decision to be made at the present time seems to be one between incineration and landfill. More specifically, incineration should replace landfill whenever the total net cost per unit (ton) for incineration is less than the total net cost per unit for landfill and other constraints (e.g., environmental quality) are met.

Represented algebraically, then

$$\left[T_i + C_i + M_i + \rho(T_l + C_l + M_l) - Z_l \right] < T_l + C_l + M_l - Z_l$$

where:

T = transport costs per unit of solid wastes

M = land costs per unit of solid waste

ρ = the coefficient of reduction of incinerated wastes

Z = the net value of other by-products per unit of waste incinerated

C = costs per unit of the actual disposal operation including capital, labor, and maintenance, but excluding land cost

l = designates land fill

i = designates incineration.

The total net cost of incineration includes a term, $\rho\ (T_1 + C_1 + M_1)$, which represents the cost of landfill for residues of the incineration process. In effect, this formulation treats landfill as the means of disposal with alternatives becoming feasible only when the savings in land and transportation costs offset the cost of the new process. Note that the value of land-saving depends on the price or rental value of land. It should also be noted that the key determinants of the optimal method, given $C_1 < C_i$, are land, transport costs, and distance. These have been key factors in the decision of large cities to use incineration (e.g., New York). Deriving an accurate measure of land cost, then, is quite important in the decision-making process as to what disposal technique would be the most efficient.

Marginal Cost

One important difficulty in the derivation of cost functions is that of finding marginal costs. Average cost, of course, does not give the true variation which will occur upon changing from one technique to another. If the average cost of landfill is discovered to be $10 per ton while that of incineration is $9, the question becomes one of whether or not it would be valid to deduct $1 for each ton incinerated rather than buried. The marginal cost of landfill may approach zero while that of incineration may well be above $10. It therefore is necessary to estimate marginal as well as average cost figures in making comparisons between alternative costs of disposal.

Summary Description of Experimental Technology

A number of disposal methods as yet in the experimental or pilot stage have been developed, which at some future time may replace or complement those currently used. The fact that these techniques are not widely used in this country limits the analysis to be made at this time to hypothetical rather than actual costs. In such cases, cost estimates made by engineers generally are based on experimental costs rather than on commercial scale-up of the experimental process.

Compaction. The experimental technique probably closest to immediate commercial application in this country is compaction at the landfill site. Compaction should be considered a complement to landfill. Refuse is fed into a compaction device which reduces it to 1/10 to 1/20 of its original volume depending on whether or not it has been ground. This may be compared to the compaction of between 1/3 and 1/4 of the original volume obtained with the conventional compaction brought about by means of tractors. Equipment required for the operation consists of the compaction unit and a shredder (or pulverizer in operations in which compaction is preceded by grinding). Probably some on-site storage would have to be provided.

The obvious by-product of compaction is more efficient land use. Given the above compaction ratios, a quantity of refuse might occupy as little as 1/5 the space it would otherwise require. Furthermore, some advantage may be realized if landfill for compacted refuse of this type settled in a shorter time than regular landfill. Future receipts for usable land could be discounted over a shorter period of time, assuming that the major constraint on the use of landfill product is settling rather than gas emission. This is another area in which more examination is needed before its costs considerations are fully realized.

Wet Oxidation. The technical aspects of wet oxidation constitute the subject of another section of this report. The information given in this section is confined to that needed to give perspective to the present discussion. Hence some repetition between this and the later section occurs. Wet oxidation possibly could be used to process a wide spectrum of organic waste found in the waste stream, as for example, manures, tree trimmings, grass clippings, sewage sludge, demolished lumber, and waste paper. The process requires facilities for storing and sorting waste materials to remove metal, glass, masonry, and plastics. The remaining organic waste must be pulverized and then suspended in water. The suspension is pressurized, mixed with molecular or atmospheric oxygen, and heated by way of heat exchange in a stainless steel reactor at 220 to 320°C under 1,000 to 2,000 psi. at about 200°C the mixture reacts spontaneously. The reactor products pass through the above-mentioned heat exchanger to heat the incoming waste mixture and then are separated into gaseous and liquid components. The gases are used to drive an air compressor, and can be used to generate electric power. The heat from the liquid component is used to heat the incoming material. Steps of the process and the necessary equipment are summarized in Table 7.

End products of wet oxidation are a number of commercially useful acids, such as acetic, formic, oxalic, and fumaric. There is also some possibility that the process could hydrolyze cellulose into glucose. Another product is a nonfibrous solid waste sludge which has a volume approximately 20% of the original material, has a high BOD, and must be disposed of in a landfill.

The economies of a 100 ton/day plant were extrapolated as in the Second Annual Report [1] on the basis of cost figures on the West-Southwest Wet Oxidation Plant of the Metropolitan Sanitary District of Chicago. Using amortization of a $3.82-million plant over 25 years with projected operating and maintenance costs it should cost around $8.78 to process a ton of solid wastes. According to the proponents of the process [1] for each 100 tons processed, some 45 tons of organic chemicals should be produced and about 10 tons of residue would have to be disposed of by landfill. Sales of chemicals produced in the process might bring in from $54 to $90 per ton of waste processed.

A note of caution is called for in evaluating these cost figures. They are based upon experimental scale only, and consequently do not include any unforeseen elements in moving from experimental to commercial size. Also, no costs of separation, storage, or sludge disposal are included. Finally, once an operation goes beyond the one-plant scale, very little may be assumed regarding price of the chemical by-products. Obviously, if every large city in the country were to turn out formic acid in waste disposal plants, the price of that acid could be expected to fall, possibly even to approach zero.

Anaerobic Digestion. A third, as yet experimental, disposal technique (anaerobic digestion) has been incidentally used in this country for many years for processing solid wastes in the form of garbage ground into the sewers by way of the kitchen or restaurant garbage grinder. Recent study has centered on the possibility of including not only garbage, but paper, wood, and glass as well. The technical aspects of this study are reported in another section of this report.

In the process, refuse is sorted, ground, and again sorted by hand and by magnet. The sorted and pulverized wastes are passed through a "grit chamber," and from there to an anaerobic digester. Digested wastes are pumped to a drying bed. The dried material can be used as a soil conditioner or as cover in a landfill. Steps and equipment for the process are summarized in Table 8.

Final products of anaerobic digestion are methane, carbon dioxide, and the stabilized residue mentioned in the preceding paragraph. Reduction in original volume is about 50%. The methane gas can be used as a fuel and thereby reduce the net cost of the digestion procedure. Again, if the system is proposed on a large scale, some account should be taken of its impact on the market for gas before computing prices and revenues from gas sales. However, in view of the ever-increasing demand for energy sources, there is little danger of a glut in the market for combustible gas.

The costs of anaerobic digestion of garbage in general are based upon estimates, and all the previous precautions concerning experimental vs. commercial scale apply here. The figures are strengthened by the fact that they are based on "off-the-shelf" equipment and existing design. Estimates range from $4 to $6 per ton [1]. However, these appear to be based on only one scale of plant for cities of various sizes, and in that respect are questionable. Also, they do not include sorting costs. Sales of the methane gas can offset the gross cost somewhat, but costs still appear high to obtain only a 50% reduction of landfill volume.

TABLE 7

LIST OF EQUIPMENT FOR WET OXIDATION PROCESS

Process	Equipment
1) Pretreatment of the raw material. (This mainly consists of removal of metal, glass, and masonry, followed by grinding of the raw material to obtain required size of particle and solids concentration.)	a) Magnetic separator. b) Ballistic separator. c) Grinding machine.
2) Storage.	a) Storage tank.
3) Pressurization.	a) High-pressure pump. b) Heat exchangers.
4) Treatment with air.	a) Air compressor.
5) Preheating.	a) Heat exchangers.
6) Oxidation process.	a) Reactor.
7) Recovery of heat.	a) Heat exchangers.
8) Phase separation. (Noncondensable gases from rest of the mixture.)	a) Expansion engine (only for a large-scale plant).
9) Filtering of slurry. (Solids portion used for landfill and liquid effluent has a fairly high BOD and so requires biological treatment.)	a) Filters.
10) Recovery processes. a) Recovery from the liquid portion of the organic chemicals. b) Recovery of carbon from the solid phase. c) Recovery of inorganic chemicals.	

TABLE 8

LIST OF EQUIPMENT FOR ANAEROBIC FERMENTATION PROCESS

Process	Equipment
1) (a) Collection of garbage.	1) Trucks
(b) Transfer of garbage to grinding machine.	2) Conveyor belts
2) Removal of nongrindable material as cans, glass, bones, etc. by hand and magnetic separation.	1) Magnetic separator
3) Grinding of garbage and transferring it to digesters.	1) Garbage grinding machine 2) Pumps
4) Digestion process.	1) Primary and secondary digesters
5) Auxiliary equipment.	1) Pumps 2) Gas meters 3) Stirring system 4) Heating system 5) Gas holder 6) Pipeline and valves 7) Automatic control system

Biological Fractionation. Biological fractionation of the organic content of solid wastes is a process for recycling materials from the wastes stream to the basic resources of the nation. It differs in concept from anaerobic digestion in that by-products of elevated economic values are produced, whereas digestion is intended to reduce volume and yield a residue which may be disposed of to the land with minimum insult to that resource. Biological fractionation produces a solid residue usable for animal feed, and glucose as an intermediate product. In this it parallels wet oxidation, the difference being that in wet oxidation the oxidation or fractionation is physiochemical; whereas in biofractionation, it is biological. The technical aspects of biofractionation are treated in a later section of this report.

In biological fractionation ground cellulosic wastes are hydrolyzed to glucose, and the glucose in turn serves as a substrate for the production of a crop of single-cell protein. Protein and the cellulosic wastes not hydrolyzed can be used as an animal feed or feed supplement. The basic difficulty of the process at present is that the cost, excluding land cost and taxes, and assuming a market for the feed supplement, approaches $42 per ton [1]. Of course, such a cost is prohibitive. However, the process is as yet in the experimental stage, and the development of additional by-products may offset the high costs to some degree. Equipment needed for the process is listed in Table 9.

Discussion. The summary given in the preceding paragraphs is not intended to lead to any conclusion regarding the optimal method or combination of methods of waste disposal, but merely to enumerate and briefly explain each process, and to point out the relevant considerations in the study of disposal costs. Indeed, it

TABLE 9

LIST OF EQUIPMENT FOR BIOLOGICAL FRACTIONATION PROCESS

Process	Equipment
1) Biological fractionation process.	a) 14-litre culture flask fermenter and bacterial culture. b) Motors for stirring the contents of the fermenter. c) RPM control unit for motors. d) Beckman pH analyzers and peristaltic pump for control of pH. e) Temperature control unit. f) Anti-foam control unit.
2) Recording of pH, temperature, and RPM.	a) Temperature, pH, and RPM recorders.

This listing is quite obviously incomplete in omitting the need for storage, sorting and disposal facilities and equipment. It was obtained from the staff paper on biofractionation. Another listing is available in the Second Annual Report on page 77 and on page 78.

Equipment	Cost	Operating Costs Per Day	
		Item	Cost
1. Medium preparation vessel, 12,000 gal. capacity	1. $ 14,500	1. Labor	$ 472
2. Medium sterilizer, 12,000 gal	2. 14,800	2. Raw Materials	60
3. Fermenter, 60,000 gal capacity	3. 115,000	3. Supervision	50
4. Centrifuges, (2), 20 in. diam.	4. 43,000	4. Maintenance	220
5. Hydrolysis vessel, 300,000 gallon capacity	5. 119,000	5. Plant Supplies	33
6. Evaporator, 8,400 gal capacity	6. 22,500	6. Utilities	340
7. Crystallizers, (4), 3,600 gal	7. 30,000	7. Overhead	260
8. Agitated tank washer, 3,600 gal	8. 14,800	8. Laboratory	60
9. Drum dryers, 50 sg ft area	9. 28,400	9. Packaging	100
10. Centrifugal pumps (6), 20 gal per minute	10. 3,000		
11. Installation cost	11. 107,500		
12. Piping	12. 155,000		
13. Instrumentation	13. 64,500		
14. Insulation	14. 34,000		
15. Electrical auxiliaries	15. 43,000		
16. Building	16. 215,000		
17. Land and improvements	17. 43,000		
18. Utilities (fixed capital equipment)	18. 107,500		
19. Engineering and construction	19. 300,000		
20. Contractor's fee	20. 75,000		
21. Contingency	21. 150,000		

should be obvious that no process will be universally ideal. Rather, conditions regarding land cost, transportation distances, and other factors will determine which process or combination should be used in any given circumstance. The object of study now ought to be to examine empirical data in order to formalize and quantify the important relationships, and to devise solutions to some of the more complicated theoretical problems, so that the foregoing analysis can be applied to actual situations.

ANALYSIS OF PRIVATE AND PUBLIC EXPENDITURES IN THE SOLID WASTES INDUSTRY—THEORETICAL AND EMPIRICAL ISSUES WITH REFERENCE TO A METROPOLITAN REGION

Need for Public Concern

The solid wastes industry comprises a host of private and public agencies. Essentially, the industry provides a service, namely, the collection, transportation, and disposal of solid wastes. The service is one whose benefits and costs cannot always be exclusively confined to those deriving the benefits by paying for the service. Benefits from adequate levels of service include the absence of waste-borne disease and of disease-carrying vectors, as well as the absence of littered streets, polluted air, uncut lawns and untrimmed gardens, which together degrade the quality of the environment. The benefits of public health and environmental quality are enjoyed by everyone in the community and they are not confined only to those bearing the cost of the requisite service. In fact they transcend private and political boundaries, with the result that neighboring households, firms, cities, and counties are essentially "together" in receiving the benefits of adequate disposal service; or, in sharing the environmental decay in the absence of such service.

The inability or inadvisability of confining the benefits of a service to those directly paying for it constitutes a basic criterion for deeming it a public good. Hence efforts toward planning for current and future provisions of the service, for establishing adequate levels of service, and of equitable methods of pricing must explicitly take into account spillover costs and benefits to the public welfare. These considerations of pervasive costs and benefits external to the industry render the usual market mechanism itself inadequate. Levels of output and methods of organization and pricing optimal from the parochial viewpoint of private firms and individuals are almost always suboptimal from the standpoint of society. A decided divergence exists between the social and the private costs and benefits that result from the public nature of the service. Broadly, the implications of this are straightforward, i.e., decisions involving the service must take cognizance of its spillover effects on public health and welfare. However, it does not imply that the service need be provided by a public agency, although the public's interest must be borne in mind while making decisions as to levels of service, pricing, and methods of organizations.*

Familiar to all social scientists are the immense problems involved in actually implementing a mode of evaluating a public good. Setting functional boundaries that even approximate areas within which costs and benefits are commensurable is a difficult venture. Also attempting to assign costs to environmental quality and the quality of life made possible by the absence of disease must ultimately involve value judgment. There are no inherently correct decisions. There may be tools to aid in the decision-making process, but ultimately someone's or one group's judgment becomes essential. So long as the value judgments are clearly stated, the socio-political haggling over objectives can be separated from analysis of particular choices; and the tools of analysis can be used to help recognize the full socio-economic impact of each alternative course of action.

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*The problem involved in finding criteria for social optima constitute an on-going and perhaps insoluble search. For some approaches to the problem the interested reader is referred to McKean's Public Spending, McGraw-Hill, 1968.

Among the aids to decision making are program budgets, cost-benefit analysis, systems analysis, and input-output analysis. These aids can be used separately or combined in a more comprehensive attempt to ascertain the magnitude of the spillovers and alternative solutions to the problem.

A final aspect of the solid wastes industry necessitating public concern derives from its interrelatedness with other urban services, and its use of land as a final repository for solid wastes residue. Any plan for urban development or redevelopment must incorporate the solid waste activity. Urban planning must allocate land for this purpose and decide upon modes of supervision in terms of long-term, comprehensive urban needs.

Cost Study Involving the Oakland Metropolitan Area

The need to explore problems in decision making regarding various aspects of solid waste management as outlined in the preceding paragraphs, and to seek for solutions, prompted a study the purpose of which was to establish a workable accounting framework and to develop operational procedures for data collection in the Oakland (California) metropolitan region. Ongoing studies in the region have brought to light several difficulties in gathering needed data, and have enabled the researchers to come to grips with analytical details. In the paragraphs to follow a brief discussion is given of the need for such a cost study and of various accounting procedures developed in the study, and report is made of progress made to data with reference to the study area.

For any study region, costs associated with the collection, transport, disposal of solid wastes, and supervision of the solid wastes industry must be determined so as to be able to arrive at the following items of information:

1. Amounts of the resources diverted to the solid waste industry;
2. Differences in cost between private and public agencies;
3. Differences in cost among areas;
4. Cost by function;
5. Costs by quantity of waste handled; and
6. Urban planning purposes.

Resources Diverted to the Solid Waste Industry

With respect to resources diverted to the solid wastes industry, the interest is in economic opportunity costs. Such costs often go far beyond that which the business community regards as "costs." For example, a scavenger company may obtain a franchise for refuse collection because it happens to own a parcel of land suitable as a disposal site. This land is "costed" by the company at the price paid for the land; or if the company already owns the land, land costs may be ignored completely. Yet, to arrive at opportunity costs, land must be considered and valued at its current market prices – amortized of course – because this is the value of the opportunities given up by using the land as a disposal site. Similarly, costs of labor, time, and transportation to and from the disposal site must be estimated for the occasional contract hauler and for individuals disposing of their own solid wastes. As can be seen, true opportunity costs frequently are hidden. Yet they must be imputed in determining the total costs of the solid wastes industry. It is important that costs are complete and treated in this manner, because only then do they yield a true picture of the resources diverted to the industry.

Cost Differences Between Public and Private Agencies and Among Collection Regions

By ascertaining the differences in cost between public and private agencies, it is possible to identify efficient methods for industrial organization. Thus, it might be more efficient for a local government to supply its own solid wastes services or to franchise a private company to do so.* Inherent differences among collection regions – industrial, agricultural, commercial, suburb, deteriorating central city, hilly, flat land – all affect the cost of service. These different areas may require different solutions as to service provision and pricing policies.

Cost By Function

Cost by function comes into play in providing a socially acceptable level of solid wastes service. Tentatively, functional categories to take into consideration are collection and transport to disposal site, the management of the disposal site itself, and the overall public supervision of the quantity and quality of service. The cost of the entire service depends on the efficiency of the methods used for each functional task. Although a single firm may provide all the functions comprising the complete service, costs must be apportioned separately to each function. Only then can alternative methods be compared.

Costs by Quantity of Wastes Handled

Preliminary investigation indicated the existence of economies of scale in the industry, i.e., the more waste handled by a firm, the smaller is the per unit cost. More evidence is needed to confirm or reject this hypothesis. This subject was considered in the Second Annual Report [1], in which a regression model based on a theoretical approach was developed.

Urban Planning Purposes

In a rapidly growing urban area, both a long- and short-run plan for collection and disposal of solid wastes are essential. Regardless of the agencies and functional methods used for disposal, some land must be set aside for this purpose. The amount and location of such land will depend on the projected growth both in magnitude and nature of composition of the disposal service area. A viable collection, transportation, and disposal system thus depends on several factors, viz., projections of kinds of growth envisioned, nature of composition of wastes generated, and a true structure of costs and their distribution. The forecasts of supply and demand needed for sound planning depend on a thorough understanding of the present system of waste generation, and on the ability to ascertain the opportunity costs associated with each subfunction in the solid wastes industry.

Relevant cost data generated by this study will give a picture of present performance in the solid wastes industry, and thereby help to decide as to "what should be" for future management.

Expected Cost Accounting and Data Collection Problems

Engaged in the collection, transportation, disposal, and supervision of solid wastes are a myriad firms which includes public agencies, private scavenger companies, private commercial haulers, and small businesses and households. Several combinations of service are possible: from private collection to public site, franchised collection to franchised site, public collection to private site, and so on. Some twelve such combinations were identified in the Second Annual Report [1].

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*This is a much debated area. See Julius Margolis, "The Demand for Urban Services," in Issues in Urban Economics, ed. Perloff and Wingo, Resources for the Future, 1967; and for private industry's point of view see "Efficient Disposal of Solid Wastes versus Obsolete Municipal Boundries," Sanitation Industry Yearbook, Refuse Removal Journal, 1969.

One of the major problems of data gathering is identifying all of the "firms" engaged in each functional activity. A second problem is in the difference in the concept of cost from the viewpoint of the firm as opposed to that of cost as needed in an economic analysis. This difference may lead to some thorny problems of data collection and interpretation. A firm's bookkeeping practices may be wholly inadequate from an economic point of view. Economic analysis requires that costs be apportioned by function. A firm may give only total costs, and find it difficult, if not impossible, to provide separate functional figures. Furthermore, some cost items may be omitted or are difficult to detect. The design of a data collection system should facilitate the recognition of total costs and their apportionment by function. A particular difficulty in tracing costs in a municipality's bookkeeping stems from the fact that the engineering, personnel, and accounting departments are each responsible for many services and activities.

There appears to be a considerable amount of reticence on the part of franchised scavenger firms in the Bay Area to divulge any information, let alone cost information. This is a frequently-encountered problem in data collection, and should not be surprising in the solid wastes industry due to its socio-legal and political environment, fear of competition, of public disapproval of land use, and of political and legal review and control.

Identifying all of the firms engaged in solid wastes collection and transportation may be difficult, since some of them conduct their business on a part-time or contract basis. In addition to those firms engaged in collection and transportation, there are the private households and small businesses that provide this service for themselves. Hopefully, the quantity of refuse discharged by these groups may be estimated on the basis of information obtained at the disposal site. Costs will have to be inputed in these cases. Inputed costs will vary between households in high and low income areas, as well as between households and small businesses. Any discrepancies should be reconciled.

Once all the agencies involved in collection and disposal of wastes or in supervision of the solid wastes industry have been identified and their costs ascertained, double accounting must be avoided in estimating true total costs. A franchise fee will be reported as a cost to the franchise holder and a revenue to the grantor. Similarly, license fees, special taxes, and disposal fees all present an accounting problem which must be met.

Some Economic Considerations

There are some purely economic aspects of the regional costs study which must be borne in mind. In a competitive industry revenues can be treated as being equal to costs. But a truly competitive industry is one wherein there are many producers of the service, and no one individual can set the price of the service which must be charged by all of the producers; nor can his output influence the market price. There must be free entry and exit from the industry, and information must be available to firms regarding opportunities. Obviously the solid wastes industry with its exclusive franchises for collection areas, its regulated disposal sites, and its frequent cost-plus pricing is not competitive. Therefore care must be taken in using the revenue and cost data that are obtained.

In economic jargon, the goal of a regional analysis is to arrive at a "cost function." This presupposes that all possible methods of accomplishing each functional activity have been identified — in other words, the production functions are known. Each production function will require a certain variety and quantity of inputs and these will have costs associated with their use.

Economic efficiency criteria require choosing that method of achieving a given objective which minimizes resource use. Cost functions yield the minimum resource cost for each production method. Given this information, decision makers can choose the production method that minimizes costs.

The relevant magnitude for decision making, as well as analysis, is marginal or incremental cost. Heuristically, this is the cost of collecting, transporting, or disposing of one additional unit. Mathematically, it is the derivative of the cost function, if it exists. So long as the cost of collecting one more unit, where unit is properly defined to fit the circumstances, is less than the marginal revenue received for collection, then it pays to expand production. Efficiency requires that the marginal cost of a product be equal to its price – where marginal cost measures the opportunity value of resources used and price the consumer's satisfaction.* However, because of the 'public good' nature of the solid wastes industry, an operational problem arises in descerning just what are true marginal costs and prices.

Producers do not pay all the costs connected with the service, – for instance, for the noise, spilled litter, or unsightliness of the disposal site. The consumer receives the spillover benefits of the service regardless of his contribution, so it is to his advantage to understate the value of this true benefit [12-14]. The result is a financing problem whose solution frequently necessitates a combination of price and tax policy. It will suffice to explicitly identify this aspect of the problem now. It will come under further scrutiny later in the research.

Production efficiency, the goal of the present research, can be viewed in both a short-run and a long-run setting. In the long run, all inputs are variable, thus permitting any scale (size) of operation. Long-run marginal cost normally declines until the most efficient scale of operation is reached. Thereafter it may increase because of increasing cost – most often due to management inefficiencies. Economies of scale refer to costs which depend solely on the size of the firm. In the extreme case, the entire desired output of an industry will be less than that which one firm could produce at maximum efficiency. This is the case of a natural monopoly. There is no evidence that the solid wastes industry constitutes such a monopoly, but there is preliminary evidence that economies of scale are present.

The scale of operation is unchangeable in the short run. Most costs are then fixed and do not enter into marginal cost analysis. Generally, overhead expenses must be paid regardless of the amount of business done, but day-to-day variable costs – especially labor – will be dependent upon the organization of production. An efficient and incentive-orientated firm accomplishes more per laborer, and thus has lower per unit costs. However, it is possible to overuse labor. This can cause costs to rise as accidents and other forms of carelessness take their toll. The trick is to expand production up to the point where marginal costs begin to rise. At that point further production is justified until price is equal to marginal cost, but this will be a phenomenon only for the short run. In the long run, efficiency criteria in the normal case dictate operation at the point of minimum marginal cost.

The nature of the solid wastes industry, with its external benefits and costs, its mixture of public and private firms, and the necessity of imputing large segments of cost, makes unsatisfactory the use of the usual efficiency criterion: "marginal cost equal marginal value of benefit (price)."

In lieu of marginal valuations there are two possible criteria of efficiency: 1) the rate of return on investment and 2) the benefit/cost ratio. (In their publication, Northern California's Water Industry [15], Bain et al. present a full discussion of the preceding criteria.) Because of the externalities problem the benefit/cost ratios probably will not be used. Instead, a rate of return test will be tried.

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[*] Technically, the marginal rate of substitution in consumption must be equal to the marginal rate of transformation in production.

The rate of return on investment is a valid efficiency criterion, provided the input market is sufficiently competitive to assume that the dollar cost of inputs measures opportunity cost. Assuming this, the average rate of return indicates the relationship between marginal value and marginal cost. Three cases can be distinguished:

1. If long-run marginal costs are constant, then the average rate of return should be the same as the applicable market rate (See a of Figure 1)

2. If long-run marginal costs are declining, the average rate of return should be lower than the prevailing market rate (See b of Figure 1)

3. If long-run marginal costs are rising, then the average rate of return should be greater than the market rate (See c of Figure 1).

Thus, if it can be ascertained that over the relevant range the average cost of handling solid wastes is constant, then a rate of return equal to the average market return for similar industries would indicate a correct allocation of resources to solid wastes.

Profits are properly considered an opportunity cost of production. They are the cost of retaining for the industry a set of resources, including entrepreneurial ability. The assumption is that resources will move to where they earn the highest return. This is perfectly valid in the long-run competitive economy and, furthermore, it is desirable. It should be pointed out that if the economy were perfectly competitive, rates of return (profit) would be everywhere the same for similar resources under similar conditions of risk. Imperfections in the market from differing degrees of uncertainty to barriers to entry result in varying rates of return. Therefore, the concept of a "normal profit" becomes ambiguous and laden with value judgment. The best that can be done in an industry like solid wastes is to choose a rate of return based on some clearly stated – and hopefully objective – criterion and call it the normal profit for the industry. Such a criterion might be what is earned by other industries using similar types of capital and having similar capital/output or capital/labor ratios.

Economic profit (π) differs from accounting profit (π^*) reported by business mainly in that economic profit recognizes the opportunity cost of capital. Thus letting R = sales revenue, C = current cost, D = depreciation and amortization, V = value of owner's equity, i = interest rate, and π = profit, accounting profit (π^*) can be written:

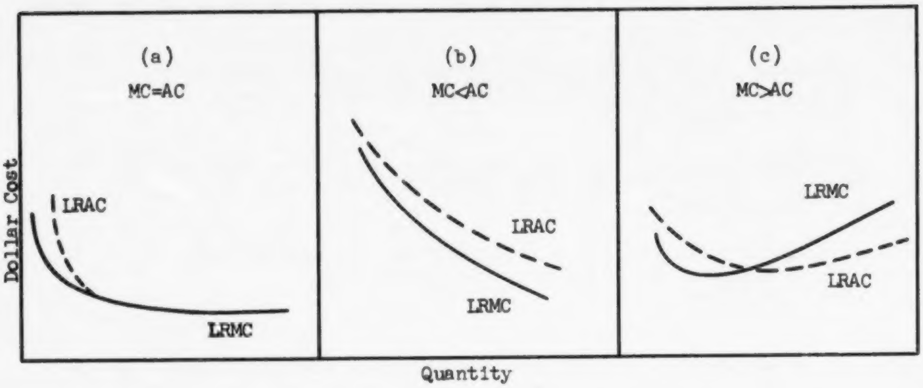
$$\pi^* = R - C - D \quad .$$

Economic profit takes account of the opportunity cost of capital and is written

$$\pi = R - C - D - iV \quad .$$

Application of a rate of return criterion requires that the relevant parameters R, C, D, and V be identified. This is frequently difficult to do since many firms, and especially public agencies, do not always distinguish between current and capital expenditures, keep no depreciation records, and are merely guessing if they set a value on their equity. The tentative acceptance of a criterion does not lessen the problem of data collection and manipulation.

Value of land deserves consideration. Land is a significant input in the production function for disposal services. It may be either privately or publicly owned, and its user may or may not be its owner. These considerations are immaterial to a valuation criterion. The opportunity cost of land, like any other resource, is its value for its next best use.



LRAC = Long-Run Average Cost

LRMC = Long-Run Marginal Cost

FIGURE I. RELATION BETWEEN MARGINAL COST AND AVERAGE COST

Consider the process of sanitary landfill in the San Francisco Bay Area. Frequently this consists of Bay fill; i.e., actually creating land by extending shorelines. Prior to landfill there was only potential value composed of surpluses-rent due to scarcity of land in the Bay Area and location rent because usable land contiguous to the water brings a market premium. Alternatively, land used for disposal sites may be too vertical for development prior to fill. In such cases the process of sanitary landfill creates usable land that immediately upon creation accrues surplus value. The net change in the value of space concomitant with landfill must ultimately be a matter of value judgment. The value of land, au natural, in preserving ecological balance must be weighed against its potential use value. Thus, a long-run view of land's opportunity cost might best be expressed as a benefit/cost ratio, where benefits are imputed as the value envisioned from a fill project and costs are the value of foregone benefits. This approach to the problem has the advantage of yielding a criterion for choosing among alternative sites, viz., the sites with highest benefit/cost ratios are chosen but this does not provide an immediate, operational method for "costing" land in the short run. For this purpose the cost of land can best be taken to be its market rental price. If this is not readily available, it must be explicitly imputed from the market prices of similar parcels.

Tentative Data Collection Procedures

General Considerations. Any data collection procedure should progress in two explicit steps. First, the purpose for which the data will be used, and by whom, must be clearly recognized. Second, the actual process by which data will be collected must be designed with due regard for the type of firm being considered. Firms in a competitive market can be approached quite differently than those in monopolistic markets. The previous sections of this paper dealt with the underlying rationale for data collection as well as some expected operational difficulties and special economic considerations pertinent to both steps one and two. In this section are reviewed some of these aspects while presenting some proposed data collection frameworks.

In the Second Annual Report three general categories of cost-sources for the solid waste industry were identified. They range from franchised scavenger companies that operate both a collection-transport service and a disposal site to individuals who provide self-service collection, transport, and disposal. Some of the possible combinations expected in the industry were listed in Table 14 of the Second Annual Report. A modification of the table is presented as Table 10 in this report.

Types of firms falling in category A operate regular collection services in which wastes are picked up at the source and are transported to recognized disposal sites. The sites may be operated by the same company that provides the collection service, or by another firm. Firms may be private or public. If private they are franchised by a public agency—city, county, or special district—to operate in that agency's jurisdictional area. Thus, all firms in this category have some form of public supervision and none of them operates in a competitive market. These firms are easy to identify, and in this case recognized public interest provides some precedent for data requests.

In category B "Firms and Individuals to Site," there are some special data collection problems. For the collection and transportation function two subgroups can be identified, commercial contract haulers and self-service individuals. The latter's costs will probably need to be imputed since they are difficult to identify. The former, if they can be identified, operate in a reasonably competitive market making it possible to accept data on their revenues as equal to costs. The decision to identify and poll individual firms in this category will be made on a pragmatic assessment of the expenses involved, budgetary limitations of the project, and benefits of so doing. If it is deemed too expensive, then these costs can also be imputed. Costs for category B firms and individuals engaged in collection and transportation can all be approached via data supplied from the sites they utilize. Hopefully the site operators will keep records on the quantity and composition of wastes deposited, and these then can be utilized to develop cost estimates. Regardless of the actual approach taken, the costs associated with collection, transport, and disposal for this category can be obtained.

Category C is conceptually vital and operationally complex. It is vital from a long-term viewpoint since some 60% of solid wastes generated does not go to regular disposal sites. During this phase of the study the entire category will be held in abeyance while efforts are directed to developing cost functions for categories A and B. Attention again will be directed to wastes not going to site when later objectives are incorporated in the study.

Data Collection for Franchised Firms. The main aspects considered in designing the following data collection frameworks were the noncompetitive nature of the industry, the need to differentiate between public and private firms, and the need to obtain or apportion data along functional lines.

From a bookkeeping point of view, expenditures (disbursements) must always equal revenues (income). The sum of all disbursements (costs of labor, capital including all equipment and its maintenance, land and overhead, plus taxes and profits) must be a figure equal to the sum of all revenues, i.e., income from services rendered plus loans or subsidies to cover any losses. Thus, it would seem that either total revenue or total expenditure could be used to ascertain costs. That this is not true, for true opportunity costs in the case of noncompetitive industries (or firms), has already been discussed in the section on economic considerations. Therefore, whenever possible the Oakland metropolitan study will approach cost determination via a firm's expenditures.

Operational exigencies can be expected to require that in some cases revenue data, and in others, expenditure data, will actually be used. This requires that double accounting be carefully avoided. If Scavenger Company A pays a disposal fee to Company B, that fee will be reported in the expenditures of A and it also will be reported in the revenues of B. It must only be counted once as a cost to the whole industry.

TABLE 10

COMBINATIONS OF COST SOURCES

Cases	Collection and Transport Agent	Disposal Site Operation
A. Franchised Firms and Public Agencies		
1. Scavenger Co. to own site.	Scavenger Co. A	Scavenger Co. A
2. Scavenger Co. to private site of another company.	Scavenger Co. A	Scavenger Co. B
3.		
4.		
5.		
6.		
B. Firms and Self-Service to recognized site.		Scavenger Co. or Public Agency
7.		
8.		
9.		
10.		
C. Firms and Self-Service to non-site.		
11.		
12.		

Firms must be differentiated as to type—public or private—to make sure that their expenditures or revenues are comparable. Public firms do not pay the franchise fees and taxes paid by private firms, and their revenues commonly include tax subsidies. Further, it is often difficult to ascertain how much of its resources a public regulatory agency devotes to the supervision of the solid wastes industry under its jurisdiction. Frequently costs of this type are not explicitly considered by public agencies; they are "hidden" in the bureaucratic structure.

To meet all of the requirements listed in this and in the preceding paragraphs, the data collection format lists detailed inputs to aid recognition of all costs.

Tables 11 and 12 illustrate the format to be used in gathering data on the expenditures made for the collection, transportation, and disposal of solid wastes. The format, based on the program budget concept, allows expenditures to be both disaggregated among the inputs and allocated to functional outputs [17 & 18]. Each row represents the expenditure made on an input, for example labor. Each column contains the expenditures made for functional output activities. Thus the total cost of labor is allocated to collection, transportation or supervision, and similarly for all inputs. Both rows and columns should add to the same figure, the total expenditure for the activity in question. Thus the bottom right-hand total when added horizontally (rows) is the output expenditures and when added vertically (columns) is the input expenditures.

The format is designed to facilitate analysis. It makes inter-firm comparisons of expenditures both by subfunction and by input costs relatively easy to do. However, to make the units comparable some common base is necessary. Therefore, data are needed on quantities of wastes handled as well as numbers of men and equipment used in the operations. These data can be requested on a separate form or incorporated on the forms as shown in the tables. In its ultimate form expenditures should be expressed in terms of per ton of refuse processed.

An alternative approach to arriving at costs for franchised firms is to utilize revenue data. The economic conditions that make this a less desirable procedure than expenditures were discussed in the preceding paragraphs of this section. Operationally this approach also is second-best, inasmuch as firms normally do not keep revenues separately for collection and for transportation to site. For analysis these operations should be separate. Moreover, revenue data would be aggregated and do not permit inter-firm comparisons. Thus expenditure data will be utilized wherever possible.

Data Collection for Firms and Individuals Transporting to Site. Disposal site operators in this category do not present problems different from those already discussed. Costing collection and transportation requires a new approach, however. Since the market can be asserted to be competitive, firms engaged in contract hauling can be polled to ascertain their revenues net of disposal fees, and these can be taken as being equal to the opportunity costs of collection and transport to site. Inasmuch as polling is a time consuming and expensive procedure when done accurately, it probably would be more feasible in the study to impute these costs on the basis of average distance to site and on average per mile haul cost for transport. Collection cost can be reasonably imputed by using an average wage rate and collection time.

The Empirical Study of Oakland Metropolitan Region

To formulate data collection procedures, identify problem areas, and generally to provide an opportunity to test and refine the procedures, a pilot study of the Oakland metropolitan region was initiated. The empirical phase of the study of the Oakland city portion is nearing completion. Progress made to date consists of defining the functional region, studying waste generation by types of wastes, and identifying several public and private agencies involved in the various functions of waste management. In the present report a brief description is given of the empirical study in its present state of progress. The compilation of actual expenditure data by function and agency within the region will be reported in a later report.

TABLE 11

FORMAT FOR TABULATION COLLECTION AND TRANSPORTATION EXPENDITURES

Firm (Name)

Type (Public/Private)

Outputs / Inputs	Collection	Transport	Supervision	Inputs Totals
Labor-direct route maintenance office administrative Labor-indirect insurance uniforms fringes				
				Labor Sub-total
Equipment rental cost trucks containers Equipment operation and maintenance gas/oil insurance repair				
				Equipment Sub-total
Office rent supplies telephone equipment Special Fees license franchise taxes professional dumping fees				
Total Output				(Rows and Columns add to total)

TABLE 12

FORMAT FOR TABULATING DISPOSAL SITE EXPENDITURES

Firm (Name)

Type (Public/Private)

Outputs / Inputs	Disposal	Salvage	Supervision	Total Cost of Inputs
Land				
Equipment:				
Amortized Cost				
Operation and Maintenance				
Labor:				
Heavy Equipment Operators				
Administrative				
Other				
Cover Material				
Total Cost of Output				Grand Total Expenditures

Description of the Study Region. The study region is the Oakland metropolitan region, a region which includes seven cities and peripheral unincorporated areas functionally related to the waste disposal industry. The area has a population of slightly more than 800,000, and an area of nearly 129,000 acres with varying population densities. Nearly 351,000 people are employed in the region in various enterprises, viz., government, services, manufacturing, and trade. Agricultural employment is insignificant, since the region is primarily urban in character. The study region is described in detail in Tables 13 and 14.

Apart from the seven city governments, a host of private and public agencies are involved in one or more functions of the waste management industry. A careful identification of these agencies revealed that they are nearly 21 in number – some private, some city, some special district, plus the county and state government. All are engaged in one or more of five different functions, viz., 1) franchised collection of household wastes, 2) collection of commercial refuse, 3) collection of special wastes, 4) disposal site operation, and 5) administration and regulation. A list of these agencies by corresponding functions in which they are engaged is given in Table 15.

In addition to the major identifiable agencies given in Table 15, there are numerous contract haulers, industries, and households that haul their own wastes to sites. In some cases, the wastes do not even reach the disposal sites. Instead, they are disposed of by other methods, e.g., agricultural wastes burned on the ground, cannery wastes either hauled to sea or dumped into a sewage system, and industrial and demolition wastes hauled to special sites not listed as disposal sites. Thus, identifiable agencies account for only a part of the total waste management industry. Consequently, there is a great need to supplement information by other sources.

TABLE 13

OAKLAND-BERKELEY METROPOLITAN AREA – POPULATION AND HOUSING[a]

City or Area	Number of Census Tracts	Names of[b] Tracts	Total Population	Household[c] Population	Occupied Housing Units			Land Area in Acres
					Single	Multiple	Total	
Oakland	99	OK 1-OK 72	377,550	369,434	76,188	64,989	141,177	35,244
Hayward Area[d]	23	HA 46-HA 68	143,550	142,028	33,148	7,993	41,141	68,035
Berkeley	28	BE 1A-BE 6E	114,000	108,796	21,303	22,440	43,743	6,663
San Leandro Area[d]	17	SL 29-SL 45	91,680	90,370	22,526	6,949	29,475	10,670
Castro Valley Area[d]	7	CV 22-CV 28	47,700	47,180	12,074	2,301	14,375	5,505
Albany	5	AB 1-AB 5	17,100	17,093	4,182	1,930	6,112	1,070
Piedmont	2	PI 7-PI 8	11,500	11,427	3,632	67	3,699	1,090
Emeryville	1	EM 6	2,850	2,831	766	315	1,081	760
Total Area	182		805,930	789,159	173,819	106,984	280,803	129,037

[a] Source: Alameda County Planning Department.

[b] Names of tracts will be subdivided, viz. 1a, 1b, 1c, etc. Therefore, names of tracts will not equal number of tracts.

[c] Household population exclude communal living groups, i.e., institutions and rooming houses.

[d] Areas are planning areas. For Hayward and San Leandro the planning area includes the incorporated cities plus unincorporated periphery area, viz. Hayward Planning Area includes San Lorenzo which is unincorporated. Castro Valley Planning Area is all unincorporated.

TABLE 14

EMPLOYMENT DATA[a]

Industry	SIC Code	Berkeley[b] Labor Market Area	Oakland[c] Labor Market Area	Hayward[d] Labor Market Area	Total Region
Agriculture	01			100	100
Construction	15,16,17	2,400	14,000	2,862	19,262
Manufacturing	19-39	8,400	51,700	6,557	66,657
Transportation, Communication, Public Utilities	40-49	2,000	25,600	1,727	29,327
Wholesale and Retail Trade	50-59	8,800	59,500	10,494	78,794
Finance, Insurance, and Real Estate	60-67	2,900	11,100	1,484	15,484
Services	70-89	13,000	45,100	10,096	68,196
Government	91-94	29,300	35,900	7,300	72,500
Other		200	900		1,100
Total Employment		67,000	243,800	40,620	351,420

[a] Employment data is from Community Labor Market Survey, State of California Department of Employment, Research and Statistics Division.

[b] Berkeley Community Labor Market Area includes Berkeley and Albany census divisions.

[c] Oakland Community Labor Market Area includes Oakland, Emeryville, Piedmont, and San Leandro census divisions.

[d] Hayward Community Labor Market Area includes Hayward and Castro Valley census divisions. Union City is outside of our study area but it is included in the Hayward census division. Mr. Bill Newton, Assistant City Manager of Union City furnished the estimates of Union City employment which were subtracted from the Hayward area totals.

TABLE 15

AGENCIES AND THEIR FUNCTIONS

Name of Agency	Function									
	Franchised Collector	Site Operation	Collects Street Sweepings	Collects Litter Cans	Collects Highway Litter	Collects from Parks and Playgrounds	Collects Commercial Refuse	Disposes of Sewage Residues	Administration and Regulation	Collects from Regional Parks
City of Albany			X			X			X	
Albany Landfill Corporation		X								
City of Berkeley	X	X	X	X		X	X		X	
Parley Batt		X								
City of Emeryville			X						X	
City of Piedmont			X	X		X			X	
Oakland Scavenger Company	X	X		X		X	X			
S + R Rubbish Disposal Company	X						X			
Turk Island Company		X								
Fibreboard Corporation		X								
City of San Leandro	X		X	X		X			X	
City of Hayward			X	X		X			X	
City of Oakland			X						X	
County of Alameda					X				X	
State of California, Division of Highways					X					
East Bay Regional Park District										X
East Bay Municipal Utility District								X		
California State Department of Public Health									X	
San Francisco Bay Conservation and Development Commission									X	
Oro Loma Sanitary District								X	X	
Castro Valley Sanitary District								X	X	

NOTE: The sign "X" indicates that the relevant function named in the column is performed by the agency indicated in the corresponding row.

TABLE 16

ESTIMATES OF WASTES RECEIVED AT THE SAN LEANDRO MARINA SITE

Owned by San Leandro City
Operated by Turk Island Co., 14222 E. 14th St., San Leandro

Haulers	cu yd/yr	lb/cu yr	tons/yr
Parley Batt from Berkeley Site	68,433	@ 400	13,687
Other Commercial Haulers	59,926	@ 250	7,491
S & R (Franchised Collector)	121,738	@ 250	15,217
Handy Can (Franchised Collector)	1,048	@ 250	131
Mfg. Industry	61,016	@ 250	7,627
Household Self-Haul	64,955	@ 250	8,119
Demolition Companies	41,948	@ 400	8,390
TOTAL	419,064		60,662

Source: Turk Island Company.

Quantity of Wastes Generated in the Study Region. The inability to identify all the waste generated in the area presents a unique problem in determining the annual quantities of wastes actually generated in the study region for planning purposes. Quantities of wastes received at the disposal sites usually are underestimated. Among the reasons behind the low estimates are methods of making estimates from daily averages and exclusion of certain wastes if they are currently salvaged. Estimated quantities of wastes from collectors represent only those from the franchised collection of wastes, and hence they also are incomplete.

Despite the difficulties listed in the preceding paragraph, an effort was made to estimate quantities of waste generation on the basis of information from disposal site operators in the Oakland area. Data obtained from the seven disposal site operators in the area were usually incomplete, and frequently were of dubious accuracy because the estimates were not based on any actual weighing of the material at the sites. Data obtained from the existing sites are given in Tables 16 and 17. Detailed data were available only for the San Leandro marina. In all other cases the data on wastes received at the site were aggregated, and were reported in summary form as in Table 17.

Judging from the data collected from the site reporters, a total of 541,300 tons/yr are produced. Using this estimate it appears that waste generation in the study region is approximately 3.4 pounds per capita per day. It should be noted the the figures on which the estimate is based are highly incomplete. To arrive at a real number for per capita generation, and to make any meaningful analysis, other sources of waste generation and collection must be tapped.

To develop a more complete and consistent set of data on waste generated in the study region, a multiplier technique developed earlier was adopted (cf. Second Annual Report). For purposes of estimation, 51 types of wastes were defined and are listed in Table 18. The types can be broadly classified as household and related (municipal wastes), agricultural, commercial and services, construction and demolition, and manufacturing.

TABLE 17

SITE ESTIMATES OF WASTES

Disposal Sites	Yearly Solid Wastes			Franchised Collector	Industrial Hauler	Commercial Hauler	Household Self-haul	Demolition
	cu yd	tons						
Albany	115,200 (Loose)		14,400	None	2,160	11,520	720	a
Berkeley	250,504 (Loose)	Rubbish Garbage	31,313 31,200 62,513	31,200	20,875		10,438	a
Davis Street	233,933 (Compacted)	Rubbish Garbage	87,725 136,000 223,725	136,000	32,897		32,897	21,931
San Leandro Marina	350,631 (Loose) 68,433 (Compacted)		46,975 13,687[b] 60,662	15,348 (Not Garbage)	7,627	21,178	8,119	8,390[c]
West Winton			144,000	54,697	44,652		44,651	a
Fibreboard			36,000	None	36,000			
TOTAL FOR THE AREA			541,300	237,245	176,909		96,825	30,321

Sources of Site Data: Albany Site: City of Albany Public Works Department; Berkeley Site: City of Berkeley Services Department; Davis Street Site: Mr. Schmidt, Oakland Scavenger Company; San Leandro Marina Site: Turk Island Company; West Winton Site: Public Health and Oakland Scavenger Company; Fibreboard Site: California State Public Health.

[a] For the Albany, Berkeley, and West Winton sites, estimates of demolition waste were not given separately but are included in the data under industrial and commercial haulers.

[b] From Berkeley Transfer Station. These 13,687 tons have already been deducted from Berkeley Site totals.

[c] Demolition density changed from 250 to 400 lb.

TABLE 18

SUMMARY OF WASTE TYPES

1 Domestic garbage and rubbish – single unit
2 Domestic garbage and rubbish – multiple unit
3 Lawn clippings and prunings
4 Septic tank residues
5 Large appliances and furniture
6 Street sweepings
7 Tree trimmings of city streets
8 Leaves
9 Litter cans
10 Trash collected along highway right-of-way
11 Sewage treatment residue
12 Residue from incineration
13 Abandoned vehicles
14 Local parks and playgrounds
15 Regional parks
16 Dirt and rubble from excavating, e.g., from BART
17 Demolition waste from razing buildings
18 Construction waste
19 Garbage from group eating facilities
20 Commercial refuse from stores, offices, public buildings, shopping centers, transportation terminals, etc.
21 Orchard prunings and dead trees
22 Crop wastes and residues
23 Manures
24 Dead animals
25 Greenhouse and nursery wastes
26 Infectious material from hospitals and clinics
27 Hazardous radioactive materials
28 Other noxious wastes, as acids, insecticides, etc.

MANUFACTURING WASTES

29 Ordnance and accessories
30 Cannery wastes
31 Other foods
32 Tobacco
33 Textiles
34 Apparel and fabric products
35 Lumber and wood products
36 Furniture and fixtures
37 Paper and allied products
38 Printing, publishing
39 Chemicals
40 Semisolids from oil refineries
41 Other petroleum manufacturers
42 Rubber and plastics
43 Leather
44 Stone, clay, glass, and concrete products
45 Primary metals
46 Fabricated metal products
47 Nonelectrical machinery
48 Electrical machinery
49 Transportation equipment
50 Instruments
51 Miscellaneous manufacturing

In general, the estimation of waste quantities (W_i) is done by a simple linear weighing system:

$$W_i = a_i X_i$$

where

W_i = the total waste generated by source i

a_i = the appropriate waste multiplier; and

X_i = the source units of waste type i. ($i = 1, \ldots, 51$).

For municipal wastes (households and related types), various source units were used in making estimates. Household wastes were estimated separately for single-family and multiple-family units; wastes from city streets, sewage treatment residue, and local and regional parks were estimated on a per capita basis, using population as a factor. Wastes from freeway and county roads were based on number of miles. In each case an appropriate waste multiplier was used. The detailed estimation procedure and the estimates are indicated in Table 19.

The production of agriculture wastes is nominal in the study region, inasmuch as the region is primarily urban in character. However, relevant estimates of agricultural wastes were made on the basis of the land use (in acres) and appropriate waste multipliers. The resulting data are listed in Table 20.

Amounts of wastes generated by commercial and service activities and by the construction and demolition industries are difficult to ascertain under present circumstances. Much remains to be learned about the nature of waste generation by these two types of industry; and the methods employed so far are as yet crude. In this study, waste from these two main types of sources were estimated by two methods. The first method involved using employment in an industry; while the second used size of city as the source unit. In each case an appropriate multiplier was used. Estimates based on employment were high and far from accurate. Estimates based on city size were more reasonable, and hence were used later in the study. The detailed calculations on wastes from commercial and service activities are given in Table 21; and those on construction and demolition in Table 22.

Manufacturing wastes were estimated by utilizing appropriate waste multipliers and employment number in relevant industries are defined by Standard Industrial Classifications. The waste multipliers were developed and reported in an earlier study [1]. Detailed calculations and the procedures used in this study are given in Table 23.

Those wastes having the highest multipliers are the ones generated by the industries falling into one of the following three categories: 1) stone, clay, glass, and concrete; 2) lumber and wood products; and 3) furniture and fixtures. As a result, these three categories apparently contribute nearly one-fourth of the total manufacturing wastes even though their corresponding employment is slightly less than 10% of that in all of the manufacturing industries. A significant portion of these wastes currently do not go to public disposal sites. It is also known that most of the cannery wastes (seasonal foods) in the study region are taken by barge for ocean disposal. Moreover, some of the wastes from paper and related industries and from the metals industries are are salvaged and recycled into the economy at the source itself. These facts influence the definition of wastes and waste multipliers, and it is possible to refine the multipliers further than has been done in this study. The problem is well recognized, and separate studies have been started to improve the waste multipliers by source. In the meantime, until better multipliers become available, estimates developed thus far should be used with caution in any actual implementation.

TABLE 19

ESTIMATION PROCEDURES AND ESTIMATES OF MUNICIPAL WASTES

Waste Source	Multipliers	Source Units	Tons/year
Household Garbage and Rubbish			
Single Family Unit	1.42910 tons/unit/year[a]	173,819[g]	248,405
Multiple Family Unit	0.62755 tons/unit/year[a]	106,984[g]	70,347
City Streets: Leaves, Litter, Sweepings, and Tree Trimmings	42.9 lb/capita/year[b]	758,230[h]	16,264[h]
Refuse Collected Along Highway Right-of-Way			
Freeway Refuse	8.0 tons/mile/year[c]	62[i]	496
County Roads Refuse	3.3 tons/mile/year[d]	200[d]	660
Sewage Treatment Residue	87.1 lb/capita/year[e]	805,930[g]	35,098[j]
Local Parks and Playgrounds	5.4 lb/capita/year[f]	805,930[g]	2,176
Regional Parks			415[k]
TOTAL WASTE			373,861

[a] Multiplier for household garbage and rubbish are from FMC Corporation Santa Clara Study, *Systems Analysis for Solid Waste Disposal by Incineration* (1968), pages 22,25. Single family unit multiplier includes estimate of refuse hauled to disposal site by householder himself.

[b] FMC Corporation Santa Clara Study, pages 52,53. The multiplier is obtained by dividing total street sweepings and tree trimming wastes (1,758 tons) by the population (82,482).

[c] Multiplier for freeway refuse developed from weight and volume data from FMC study.

[d] Multiplier for county roads refuse computed from information about mileage and volume of refuse, which was supplied by Road Division of Alameda County.

[e] FMC Corporation Santa Clara Study, page 51.

[f] FMC Corporation Santa Clara Study, pages 54,55.

[g] Estimate of population and occupied housing units are from Alameda County Planning Department and are for July 1967. The population of Castro Valley, and unincorporated area is excluded from this total. Its street refuse is listed under county roads refuse.

[h] Excluding Castro Valley street sweepings.

[i] Data on total freeway mileage in the county was supplied by State of California Division of Highways, District 4. The study area's proportion of the county total (57%) was determined by use of a contour meter.

[j] Including Castro Valley street sweepings.

[k] Mr. Lynch, Acting Chief of Maintenance Department, East Bay Regional Park District.

TABLE 20

AGRICULTURAL WASTES

	Source Units[a]	Multiplier	Tons/year
Apricots	310 acres	1.5420 tons/acre/year[b]	478
Cherries	53 acres	1.4265 tons/acre/year[b]	76
Vegetables, berries, and seed crops	3,614 acres	3.0 tons/acre/year[c]	10,842
Greenhouse and nursery	125 acres	25.0 tons/acre/year[d]	3,125
Feedlot cattle manure	840 head	13.21 tons/head/year[e]	11,096
TOTAL AGRICULTURAL WASTE			25,617

[a] Basic crop acreage and livestock inventory is from Alameda County Agriculture Commission Report (1967). Data was allocated to subcounty areas with help of Alameda County Agriculture Extension Office.

[b] Apricot and cherry orchard waste multipliers determined by estimate of trees per acre from University of California Agricultural Extension Service and per tree waste multipliers from FMC Corporation Santa Clara Study.

[c] State of California Department of Public Health, Status of Solid Waste Management in California, 1968. We used an average of the five multipliers given for field and row crops on page III-17.

[d] Professor Harry C. Kohn, Department of Environmental Horticulture, Davis Campus of the University of California. (Verbal Communication).

[e] The manure multiplier for cattle is from Taiganides, E. Paul, Table 4, Agricultural Solid Wastes. Three of the cattle manure multipliers in his table averaged to 72.4 lb/day.

TABLE 21

ALTERNATE ESTIMATES OF WASTE GENERATED BY COMMERCIAL ORGANIZATIONS AND SERVICES[a]

	Size of City Population	Waste Multiplier lb/cap/day	Applicable Population	Waste tons/yr
(1)	> 100,000	3.5[b]	635,100	405,670
	10,001 - 100,000	2.5[b]	167,980	76,641
	1,001 - 10,000	2.0[b]	2,850	1,040
			805,930	483,351
(2)	3.81011 tons/employee/year[c] x 265,401 employment =			1,011,207

[a] Standard Industrial Classification 40 - 94.

[b] Dept. of Public Health, State of California, Status of Solid Waste Management in California, 1968.

[c] Multiplier developed from employment data from Dept. of Employment and unpublished data from FMC Corp. Santa Clara Study.

A summary of waste quantities by waste sources is given in Table 24. On the whole, the study region accounted for nearly 1.52 million tons of solid wastes, or nearly 10.3 pounds per capita during the year 1967-68.

To make further comparisons of waste generation as based on multipliers with costs and quantity estimates obtained from agencies listed in Table 15, it was necessary to disaggregate the regional totals (Table 24) by subregion.

Eight subregional areas were recognized: namely, the cities of Albany, Berkeley, Oakland, Piedmont, Emeryville, and San Leandro, and the Castro Valley and Hayward areas. Efforts are being made to allocate wastes by source to each of these subareas. Neither Castro Valley nor Piedmont has any manufacturing industry, and Albany accounts for very little. Most manufacturing is done in Oakland, San Leandro, Hayward, and Emeryville, although Berkeley has some food processing, chemicals, metals, machinery, and "miscellaneous" industries.

A comparison of the estimates given by site operators with those derived with the use of statistical multipliers indicates that some 6.91 pounds per day per capita currently were not going to disposal sites. This amounts to 67% of the generated waste not going to the site — a significant figure to be considered in all future management and control of disposal activities.

TABLE 22

ALTERNATE ESTIMATES OF WASTES GENERATED BY CONSTRUCTION AND DEMOLITION[a]

Size of City Population	Waste Multiplier lbs/capita/yr	Applicable Population	Waste tons/yr
> 100,000	500[b]	635,100	158,775
(1) 10,001 - 100,000	250[b]	167,980	20,997
1,001 - 10,000	100[b]	2,850	142
			179,914
		805,930	(rounded) 180,000
(2) 41.25205 ton/employee/year[c] x (19,262) employment =			794,597

[a] Standard Industrial Classes 15, 16, 17.

[b] Dept. of Public Health, State of California, Status of Solid Waste Management in California, 1968.

[c] Multiplier developed from construction employment data from Dept. of Employment and unpublished data from FMC Corp. Santa Clara Study.

Given the present state of knowledge concerning the study region and solid waste estimates, based on multipliers, the following considerations should be mentioned:

1. Salvage operations need more investigation;
2. Some types of waste are disposed of by other than landfill, i.e., such as products that are burnable, e.g., furniture;
3. Demolition wastes are frequently used as base-fill;
4. Multipliers using population as a weight factor would probably benefit from further disaggregation based on incomes;
5. Manufacturing estimates require further research.

The above considerations will be borne in mind and remedied as far as possible before further work on the analysis of private and public expenditure is continued.

TABLE 23

MANUFACTURING WASTES

Industry	Employment[a] July 1967		Multipliers[b] tons/employee/year	Waste tons/year
Seasonal Foods	2,200		5.56570	12,245
Other Foods	11,482		4.81655	55,304
Total Food Products		13,682		
Paper, Printing, and Publishing		6,478	12.87060	83,376
Chemicals		1,900	8.21075	15,600
Textiles and Apparel	2,193		.52575	1,153
Rubber and Plastics	1,835		1.54810	2,841
Leather	355		2.49365	885
Total Other Nondurables		4,383		
Stone, Clay, Glass, and Concrete		3,708	18.11425	67,168
Primary and Fabricated Metals		15,250	6.7300	102,632
Electrical and Nonelectrical Machinery		12,478	3.58040	44,676
Lumber and Wood Products	1,033		21.68805	22,404
Furniture and Fixtures	1,562		20.15545	31,483
Transportation Equipment	2,768		3.39330	9,393
Instruments	915		2.51700	2,303
Total Other Durables		6,278		
Other Manufacturing		2,500	2.49365	6,234
TOTAL MANUFACTURING EMPLOYMENT		66,657		457,697

[a] Basic employment data is from the State of California Department of Employment Community Labor Market Survey. Data was adjusted to exclude Union City which is not in the study area. Employment in the categories "Other Durables" and "Other Nondurables" was distributed to the relevant SIC groups by using the same proportions as existed in the 1965 employment data from ABAG.

[b] Multipliers for the manufacturing industries were developed and reported in Table VI, Comprehensive Studies of Solid Waste Management, Second Annual Report. The multiplier for the category Paper, Printing and Publishing (SIC 26 and 27) is a simple average of the separate multipliers for SIC 26 and 27. Also, the multiplier for the category Electrical and Nonelectrical Machinery (SIC 35 and 36) is a simple average of the separate multipliers for SIC 35 and SIC 36.

TABLE 24

SUMMARY OF ALL WASTES GENERATED IN THE OAKLAND METROPOLITAN AREA

Waste Source		
MUNICIPAL		
Single Family Unit Housing	248,405	
Multiple Family Unit Housing	70,347	
Street Sweepings and Other Street Refuse	16,924	
Sewage Treatment Residue	35,098	
Local Parks and Playgrounds	2,176	
Regional Parks	415	
Refuse from Highway Right-of-Way	496	
		373,861
Construction and Demolition Waste		180,000
Commercial and Public Facilities		483,351
AGRICULTURAL		
Orchard Prunings	554	
Crop Wastes and Residues	10,842	
Manures	11,096	
Greenhouse and Nursery Wastes	3,125	
		25,617
MANUFACTURING		
Cannery Wastes	12,245	
Other Foods	55,304	
Textiles and Apparel	1,153	
Lumber and Wood Products	22,404	
Furniture and Fixtures	31,483	
Paper, Printing, and Publishing	83,376	
Chemicals	15,600	
Rubber and Plastics	2,841	
Leather	885	
Stone, Clay, Glass, and Concrete Products	67,168	
Primary and Fabricated Metals	102,632	
Electrical and Nonelectrical Machinery	44,676	
Transportation Equipment	9,393	
Instruments	2,303	
Miscellaneous Manufacturing	6,234	
		457,697
TOTAL		1,520,526

A METHOD OF OPTIMAL SITE SELECTION AS APPLIED TO SOLID WASTE MANAGEMENT

General Remarks

The problem of determining the optimal location of waste generating points and disposal sites was discussed in Chapter IV of the Second Annual Report [1]. The original formulations of the procedure for obtaining the optimum solution were necessarily theoretical; and hence, certain assumptions were made to ensure that the optimization procedure would not be unduly complicated. These assumptions have since been subjected to the realities of solid wastes management, and corresponding improvements and variations of the original formulation have been made and were issued in the form of special reports by El-Shaieb [19] and Stern [20]. In this section, one variation of the network flow model is applied to the nine-county San Francisco Bay area. The area has 116 waste generating points and 60 disposal sites. The program developed and applied herein is still experimental in nature, but it serves to illustrate the applicability of the mathematical model for a practical situation. The procedure described herein could be considered as a short-run solution to a waste disposal situation in which landfill is the overriding method of disposal and the transportation costs are of greater concern than those for disposal.

Introduction

The main problem considered by El-Shaieb [19] was as follows: Given a set of destinations n, their cartesian coordinates of locations (x_i, y_i) $(i = 1,\ldots,n)$ and their requirements w_i, the problem was to find 'm' disposal sites located at (x_j, y_j) $j = 1,\ldots, m$, such that the cost function $F(x,y)$ is minimized, where:

$$F(x,y) = \sum_i \sum_j \alpha_{ij} w_i \ell_{ij}$$

ℓ_{ij} = the distance, or unit cost, between destination i and source j and is taken as:

$$\left[(x_i - x_j)^2 + (y_i - y_j)^2\right]^{\frac{1}{2}}$$

$\alpha_{ij} = \{$ 1 if the destination i is assigned to source j; or 0 otherwise.

Let $F(\alpha_{ij}) = \sum_i \sum_j \alpha_{ij} C_{ij}$

Defining $C_{ij} = w_i \ell_{ij}$, the problem is reduced to finding (α_{ij}), such that $F(\alpha_{ij})$ is minimized subject to the conditions on $\alpha_{ij}\ldots(i=1,\ldots,n,$ and $j=1,\ldots,m)$. When 'm' is greater than one, the problem is usually referred to as "the multiple source location problem" in operations research literature.

El-Shaieb developed a branch and bound procedure that constructs source and destination sets by adding one location at a time. Once a feasible set has been established, the objective is to reduce the number of feasible source sets constructed in order to reach the optimal solution.

Before applying the El-Shaieb definition and procedure to the present problem in solid wastes, it should be noted that the usage of the terms "destinations" and "sources" as conceived in operations research language is somewhat confusing to the present application. The word "destination" is changed to mean the "waste generating point" (or simply the "generating point") and the work "source" is changed to mean "disposal site" (or simply, "site").

Modifications of the Problem

The general network flow model as described in the preceding paragraphs considers all points as both potential generating point and disposal site. This, of course, is unrealistic, and obviously there is need to modify the original formulation. Moreover, a distinction should be made between existing disposal sites and potential disposal sites. The potential sites may or may not be selected by the procedure employed. There is some argument with respect to the fixed cost of opening new disposal sites, and also to variation in the operating costs by capacity of the existing sites. These arguments are not emphasized in the present formulation, and will be considered in later studies. The problem now is to recognize the existing disposal sites in operation and the set of potential sites from which to choose and then to arrive at the optimal solution.

The above factors lead to the modification of the original formulation. The following model is now defined for application:

Let

S = set of all existing disposal sites, (= s)

P = set of all potential locations where disposal sites could be established, (= p)

D = set of waste generating points, (= n)

m = set of additional (potential) disposal sites to be located out of P. (m is a criterion number specified outside the model).

The objective of the revised model is essentially that of the previous model, i.e., to minimize the cost function $F(\alpha_{ij})$. An important difference, is that the optimization program will consider all possible flows from all 'i' to all 'j' where $(i=1,\ldots,n)$ and $(j=1,\ldots,s+p)$ and i not equal to j, inasmuch as a given location cannot be both generating point and disposal site. The change then is:

Minimize:

$$F(\alpha_{ij}) = \sum_{i=1}^{n} \sum_{j=1}^{s+p} \alpha_{ij} C_{ij}$$

Subject to:

$$\alpha_{ij} = \begin{cases} 1 \text{ if generating point } i \text{ is assigned to site } j \\ 0 \text{ otherwise.} \end{cases}$$

The various assumptions underlying the mathematical model, along with their implications on the real world situation, are treated in the paragraphs which follow. It is recognized at the outset that the assumptions are more or less "enabling" and are fashioned to accommodate the present programming technique. In future work, each of these enabling assumptions will be relaxed to make the model more widely applicable.

Assumption 1 – The unit transportation costs are independent of the amount shipped. This assumption is fairly common and any suitable transportation cost function can be used.

Assumption 2 – The optimal number of disposal sites (m) to be chosen from P (the set of potential sites) are given. This assumption is dictated by the nature of the algorithm used rather than by any theoretical considerations.

Assumption 3 - Fixed cost of opening a new disposal site is negligible or zero. This assumption is convenient; but if it were true at all times, then the question of which new disposal sites should be opened and at what time intervals becomes trivial. The total transportation costs will not be increased by mearly opening a site as long as there is no shipment to that site. To circumvent this difficulty, some schedule must be selected for the selection of new sites, m, during the designated time period. In this study it is assumed that one new site is made operational each time the capacity of an existing site is exhausted. This number could easily be two, three, or any number. Although this seems arbitrary it does have the merit of practicality. The fixed cost of opening sites could be considerable, and only one new site can be opened by each city or public agency due to budget restrictions. It is therefore realistic to assume that only a limited number of potential sites can be opened at a given time.

Assumption 4 - The time over which the optimum schedule is desired is assumed to be 75 days. The time horizon over which the optimum schedule is based is one of expediency. This target data could well have been five years if that were desired. For the present, 75 days is used as an illustrative target date. The selection of a particular planning horizon does not influence the program itself. If a large horizon like five years were to be chosen, then the corresponding average waste generated during the period would have to be used with similar changes in the transportation costs for each different year, month, or day, if desired. This can be easily accommodated in the program by causing a certain elapsed time to trigger the reading of the new set of data. These trigger dates can be chosen at random. Since the new set of data represents an average over the previous elapsed time, it is strongly suspected that the optimum solution obtained may be a qualified one and may vary with the time horizon chosen.

Another effect of a longer time horizon would be to require a more elaborate cost matrix. In the present problem quite a few distances from generating points to sites were chosen as infinite, and thus the generating points were allocated to the few nearby sites. This is possible in the short run where the site capacity may not be exhausted. However, if a longer time horizon, such as five years were to be chosen, then the number of possible flows would increase enormously and a larger transportation cost matrix would be required.

Thus the choice of time horizon may affect the optimum solution in two ways: 1) by necessitating different averages to be triggered at frequent time intervals; and 2) by increasing the number of possible network flows to be examined. The effects of planning horizons are stated as possible hypotheses for future experimentation.

Assumption 5 - There are no capacity restrictions on the disposal sites. This is one of the most important of the assumptions. To a great degree it determines the programming procedure used in this study. Though the disposal site capacities are in fact recognized at a later stage (when a site is filled) and rescheduling is done, the actual allocation of generating points to sites is done on an instantaneous or minute-to-minute basis. In other words, the program developed and used in this study treats each disposal site as if it has infinite capacity, up to the very moment it is exhausted. This assumption of no capacity restriction does indeed give a qualified optimum (suboptimum). Its implications are described in the next section (Procedure).

Procedure

With the mathematical program as developed in the present study, locations of disposal sites are chosen which should be made operational out of a given number of possible potential sites. The program does not provide for considerations of any scheduling requirements on the transfer vehicles carrying solid wastes from the generating points to the disposal sites. It is assumed that enough transfer vehicles are available for doing the job. The program recognizes the already existing sites, S, and then chooses the specified number, m, of new potential sites from a set of given potential sites, P, such that the total transportation costs are minimized. When the fixed capacity of the disposal sites is recognized, it may so happen that some of the sites may be filled before the target date. The program output specifies when that eventuality will take place, which disposal site is closed, and how the new allocation will affect the scheduling of wastes from generating points to new disposal sites.

The method of recognizing capacities of disposal sites described in the preceding paragraph raises a procedural question which is yet to be resolved. The allocation or scheduling of wastes to sites is done in this program on a minute-to-minute (or instantaneous) basis rather than on a realistic time horizon. The program treats each site as though it had infinite capacity up to the very moment it is exhausted.

The mathematical calculations involved a complete enumeration of all possible combinations of m out of P potential sites and corresponding allocation of flows to take place. As P increases, the number of necessary computations also increases rather rapidly. Accordingly, a branch and bound technique was employed. The technique reported herein is a modification of the earlier version given by El-Shaieb. The object of this procedure is to reduce the number of feasible sets constructed from P in order to reach the optimal solution. After considering the various combinations of potential sites and tacking them on to the existing set of sites, only those sets were considered which met the feasibility requirements, i.e., select m out of P. Lower bounds were established to select the most promising of these, and actual evaluations were then computed for them. The set with the lowest actual evaluation was then chosen as the current candidate. The steps involved in arriving at the evaluation are given in Appendix A. All sets with a lower bound greater than this evaluated value were dropped from further considerations. The procedure was repeated until there were no more sets with a lower bound less than the evaluated actual value associated with the current candidate set. Although at the time of the scheduling no explicit assumption of the site capacity was made, it was later introduced to make it possible for the branch and bound technique to work.

The method of treating the fixed capacity of sites as applied in this study is perhaps the most serious limitation of the present approach. The following illustration emphasizes the consequences of such a procedure: Suppose that two waste generating points, A and B, both initially minimize transport costs by shipping their respective wastes (W_1 and W_2) to disposal site (1). Assume, further, that the capacity of site (1) will become exhausted halfway through the nominal planning period, and that the cost differential between shipping to site (1) and shipping to the next best alternative is for A, \$2.00 per truckload; and , for B, \$5.00 per truckload. Assuming that the constraint on the second best alternative for A is not effective, it is obvious that existing capacity in site (1) should be allocated as much as possible to wastes coming from generating point B, leaving A only that capacity which remains after B's requirements were satisfied at any given time. The program described earlier, in which the minute-to-minute scheduling horizon is used, does not recognize the capacity constraint until it is reached, and so ships to site (1) all wastes from A and B. It then designates the next best route for both A and B when the capacity of site (1) has been exhaused.

The questions remaining for further investigation are the following: Does the planning horizon affect the optimum solution? Similarly, does the definition of the functional boundary to include or exclude a particular waste generating point also affect the optimum? In other words, is the total transportation cost minimized over the entire nominal planning period for any given functional boundary? Efforts now are under way to investigate these questions and to lessen these limitations in the future. For the moment, a choice must be made between using the method to obtain a qualified suboptimum; or to experiment with a very large number of generating points and sites and propose different definitions of planning horizons and functional boundaries, and even so achieve perhaps only a marginal reduction in transportation costs.

To recapitulate, the present program assumes no fixed cost of opening new disposal sites, sets up a hypothetical planning period for scheduling, and provides a rough procedure for recognizing site capacity restrictions. Some real world situations will be introduced later in the research program, and thereby relax the assumptions listed earlier.

Application of the Modified Algorithm to Solid Waste

As is evident from the preceding formulation, to limit the size of the problem, the application of the model requires data on location of waste generating points, existing disposal sites, potential sites, quantities of wastes shipped to site, transportation distances and unit costs, site capacities, and finally the target date.

Selection of Disposal Sites and Waste Generating Points. The present study is being carried out with reference to the nine-county San Francisco Bay region, viz., Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, and Sonoma counties.

Viewed in general framework, the problem of collecting solid wastes from each and every home in a city is in itself a large and complex transportation and scheduling problem. For the purposes of this study, it was assumed instead that all wastes in a city were generated at a central point (centroid) from which they were shipped to a disposal site. In the present study, this central point — representative of the city — was usually taken as the downtown section. The only exception to this procedure was with respect to the city and county of San Francisco, which was broken up into 12 different sectors and each sector treated as a city by itself. Further refinement is possible by treating larger cities like Oakland and San Jose as a cluster of small cities — as was done in the case of San Francisco. However, this was not done, because to have taken such a step would have resulted in making the problem unmanageable.

As far as the disposal sites were concerned, no major assumptions were involved. The sites were also treated as points, but the extent of approximation involved here is negligible when compared to assuming a city as a single generating point.

The entire San Francisco Bay Area region was thus broken up into 116 generating points. For detailed discussion, see the Second Annual Report. For the existing sites the latest report put out by the California State Department of Public Health [21] was used. Since the reference period for the study reported herein was chosen to be 1966-67, all sites with a remaining capacity of 10 acre-feet or less at that time were neglected, because it was assumed that they would be used up by the time this report was under way. All special sites (which receive only special wastes such as demolition wastes, liquid industrial waste, etc.) were also ignored, since they would not be relevant for the purposes of solid wastes considered in this study. In all, the available, currently existing disposal sites were reduced to 60 in number; for which corresponding data on wastes, population, etc., were developed.

The potential sites were chosen from among the various proposed general sites pending approval from the local public health agencies. Sites most likely to be approved were chosen to serve as potential sites. In addition, some of the currently existing cities, whose capacities could be easily increased by the acquisition of land nearby, were considered as potential sites. Thus, a total of 14 potential sites were selected.

The Cost Matrix, C_{ij}. The cost matrix, C_{ij}, gives the unit transportation cost of hauling wastes from generation point i to the disposal site j. Though transportation cost was expressed in terms of distance in the earlier formulation, the actual program was formulated in terms of travel time. Therefore, the cost matrix C_{ij} will be developed from a distance matrix ℓ_{ij}, which is then translated into travel time.

The waste generating points and disposal sites were plotted on the map, and the distance ℓ_{ij} was chosen as the minimum distance over major roads leading from generating point i to disposal site j. Freeways and major arterial routes were generally perferred to minor roads because it was felt that distance saved on the latter would be more than offset by increased travel time. Since 74 x 116 measurements on the map would have been required to form the complete ℓ_{ij} matrix, a simplifying assumption was introduced. Actual measurements were made only for a few sites nearest to the generation point under consideration, while distance was assumed to be forty miles for all other sites. An average of seven or eight actual measurements were taken for each city. The number varied from as low as three to as high as fifteen, depending on the amount of waste generated by that city. For example, it was felt that a city like San Jose, which produces 1,272 tons of waste per day, should be given a wider range of choice regarding disposal sites than should be given to St. Helena, which produces only 6.9 tons per day. If in the solutions a certain city had been alloted to one of the distant sites, more actual measurements would be included for that city and the program would be rerun. It must be noted, however, that this procedure was followed only for convenience and to reduce unrealistic combinations. It in no way affects the generality of the program itself.

Once the distance matrix (ℓ_{ij}) was established, it was converted to transportation time involved for the round trip by using a plot of the average haul speed vs. total haul distance as developed in SERL Bulletin 8 [5]. In Table 25 are given pertinent data excerpted from the Bulletin. This process allows computation of travel time with a nonlinear relationship to distance. The data compiled therein were obtained prior to 1952 and consequently the average speed figures used here probably are outdated. However, because the purpose of the study is to demonstrate the application of an algorithm rather than to derive immediately useful results, the discrepancies are ignored as irrelevant for the moment. It should be noted that the transportation time was developed for the round trip, inasmuch as the transfer vehicles and men would be tied up for this duration of time. To calculate the cost per ton of transporting solid wastes, the following formula developed by Dair [22] was used. The cost is based on a standard 6-ton truck with a 2-person crew as follows:

$$\text{Cost per ton per minute} = \left[\frac{\$(2.55 + 0.325\,S + 5.40\,L + 0.95)\,t}{(S)\,60}\right]$$

Where: t = travel time in hours, S = tonnage of solid wastes hauled, and L = labor (man-hours). Using the above formula, the cost/ton/minute is obtained as (0.04514 t), substituting S = 6 tons and L = 2 (man-hours).

For any particular flow of solid wastes, i.e., from generating point i to site j, the total transportation cost is estimated by inserting the appropriate estimate for 't' in the expression (0.04514 t). The actual cost matrix, sometimes referred to as the distance matrix, as estimated in the present study consists of slightly more than 1,000 elements. The elements are already undergoing revision for a later study and hence they are not included in this report.

Solid Wastes: Generation points (i) and amounts generated (W_i). The amount of solid wastes generated at the point 'i' and transported to any of the disposal sites is represented as W_i. The generation point could be a complete city or a part of it, or an urban area not incorporated into a city. The primary source for developing W_i is the information tabulated in the Second Annual Report (cf. Table 2, page 19 of the report). The procedure used in estimating W_i is given in the paragraphs which follow.

TABLE 25

TRANSPORTATION TIMES FOR COLLECTION

One Way Haul Distance in Miles	Average Speed in min/mile	Adjusted Travel Time in Minutes Round Trip	One Way Haul Distance in Miles	Average Speed in min/mile	Adjusted Travel Time in Minutes Round Trip
0.5		18.5[a]	16.0	1.88	60.0
1.0		20.5[a]	16.5	1.82	60.0
1.5		22.5[a]	17.0	1.76	60.0
2.0		24.5[a]	17.5	1.70	59.5
2.5		26.5[a]	18.0	1.64	59.0
3.0		27.5[a]	18.5	1.58	58.5
3.5	4.10	28.5	19.0	1.53	58.0
4.0	3.60	29.0	19.5	1.48	57.5
4.5	3.35	30.0	20.0	1.44	57.5
5.0	3.22	32.0	20.5	1.41	58.0
5.5	3.15	34.5	21.0	1.39	58.5
6.0	3.09	37.0	21.5	1.38	59.5
6.5	3.01	39.0	22.0	1.38	60.5
7.0	2.96	41.5	22.5	1.37	61.5
7.5	2.90	43.5	23.0	1.37	63.0
8.0	2.84	45.5	23.5	1.36	64.0
8.5	2.78	47.5	24.0	1.36	65.5
9.0	2.72	49.0	24.5	1.35	66.0
9.5	2.66	50.5	25.0	1.35	67.5
10.0	2.60	52.0	25.5	1.35	69.0
10.5	2.54	53.5	26.0	1.35	70.0
11.0	2.48	54.5	26.5	1.35	71.5
11.5	2.42	55.5	27.0	1.35	73.0
12.0	2.36	56.5	27.5	1.35	75.5
12.5	2.30	57.5	28.0	1.35	77.0
13.0	2.24	58.0	28.5	1.35	78.5
13.5	2.18	59.0	29.0	1.35	79.5
14.0	2.12	59.5	30.0	1.35	81.0
14.5	2.06	59.5	40.0	1.35	108.0
15.0	2.00	60.0	50.0	1.35	135.0
15.5	1.94	60.0			

[a] Represents extrapolated values.

In the earlier study of the nine-county San Francisco Bay area, the study region was divided into 42 functional boundaries, each of which was termed a "Disposal Service Area" (DSA). The concept of DSA was very useful in compiling consistent and comparable information on wastes generated and the wastes generators. This information was further broken down to estimate waste flows from each generating point. In this study, the 42 DSA's have been broken down into 116 waste generating points ($i=1, \ldots, 116$) and the waste data have been updated to correspond to a more recent year, namely, 1968. The actual procedure is described below.

Consider for example, the Oakland DSA (code No. 0102). This DSA accounts for about 1,652 tons of solid wastes generated per day. The wastes include mostly population-oriented wastes and some commercial wastes. First, the waste figures were reduced to correspond only to household or population-oriented wastes; i.e., the waste figure 1,652 was reduced to the 1,602 tons assumed to be generated by the population (692,000) within the DSA. The DSA consists of 10 waste generating points, some complete cities such as Hayward, Piedmont, and Albany, other partial cities such as Oakland and Berkeley, and other urban areas such as Castro Valley and San Lorenzo which are not within city boundaries. The total population of the DSA (692,000) was further broken down by these generating points. These population figures were used to apportion the total wastes (1,602 tons/day) among the 10 generating points. Similarly, the other 41 DSA's were broken down, with all 116 waste generating points established within the nine-county San Francisco Bay area. All of the above calculations are summarized in Table B-1 of Appendix B. The waste data in the table pertain to 1966. The waste figures were updated to 1968 on the basis of population growth and the updated numbers incorporated in Tables B-2 and B-3 of Appendix B.

Remaining Capacity Vector. This represents the capacity remaining to be used in the existing and potential disposal sites as of July 1968. The original capacity referred to 1966. These were updated again to reflect the capacities remaining as of 1968 by using the rate at which they were receiving solid wastes in 1966. For the potential sites this means the available capacity when that potential site becomes operational. In the case of some of the potential sites, where no capacity figure was available, the capacity was assumed to be very large, namely 15,000 acre-feet. The capacity data in acre-feet were converted to tons, using an average density of 600 cu yd per ton of solid wastes. The detailed calculations are given in Appendix C.

Discussion of Results. The output of the program run under the condition that one new site be opened for each existing site closed down is listed in Table 26. It can be seen from the results as listed in the table that the program stipulates to which site the generating points should ship their wastes when their existing flows cannot be accommodated from the present site. For example, at the end of the first 15 days, the disposal site coded 16 is filled to existing capacity, and a new site, No. 3, should be opened. At the end of 61 days, site No. 43 is closed, and a new site No. 7 is opened. The various allocations of waste generating points, closing down of particular sites and opening of new sites, are described in Schedules 1 through 5 until the target date of 75 days is reached.

Since it is stipulated that at least one new site be brought into action for every existing site closed down, limitation is placed upon the practicability of the solution so obtained because it maintains at least as many sites operational as existed at the start. This may not be a desirable situation, and the reason for being forced into it concerns the limitation of the theory employed and hence the program. It should also be noted that the theoretical model does not mention the fixed costs involved in opening up a new site. If fixed costs are also taken into account, then the added decision of whether to open a new site and when it should be opened can be built into the program itself. Unfortunately, very little has been done so far in this area to include fixed costs of a site along with finite capacity of the sources and make it operational for a large enough study area.

TABLE 26

OUTPUT OF THE PROGRAM UNDER THE CONDITION THAT ONE NEW SITE BE OPENED FOR EACH EXISTING SITE CLOSED DOWN

Generating Point Number	Wastes Should be Shipped to the Following Site Numbers					
	Schedule One	Schedule Two	Schedule Three	Schedule Four	Schedule Five	
This schedule will be in effect from day 'a'	0.00	15.21	61.21	67.00	73.95	
to day 'b'	15.21	61.21	67.00	73.95	Target date	
This schedule results in closing of site number ⟶	16	43	29	73	-	⟵ on day 'b'
opening of site number ⟶	3	7	6	9	10	⟵ on day 'a'
1	66	66	-	-	-	
2	63	63	-	-	-	
3	64	64	-	-	-	
4	64	64	-	-	-	
5	65	65	-	-	-	
6	62	62	-	-	-	
7	68	68	-	-	-	
8	33	33	-	-	-	
9	32	32	-	-	-	
10	31	31	-	-	-	
11	31	31	-	-	-	
12	70	70	-	-	-	
13	69	69	-	-	-	
14	70	74	-	-	-	
15	74	74	-	-	-	
16	74	74	-	-	-	
17	70	70	73	-	70	
18	72	72	-	-	-	
19	72	72	-	-	-	
20	71	71	73	-	71	
21	71	71	-	-	-	
22	71	71	-	-	-	
23	72	72	73	72	-	
24	22	22	6	-	-	
25	24	24	-	-	-	
26	24	24	-	-	-	
27	24	24	-	-	-	
28	26	26	-	-	-	
29	26	26	-	-	-	
30	26	26	-	-	-	
31	26	26	-	-	-	
32	26	26	-	-	-	
33	26	26	-	-	-	
34	23	23	-	-	-	
35	65	65	-	-	-	
36	26	26	-	-	-	
37	26	7	-	-	-	
38	16	15	-	-	-	
39	62	62	-	-	-	
40	15	15	-	-	-	
41	27	27	-	-	-	
42	27	27	-	-	-	
43	27	27	-	-	-	
44	15	15	-	-	-	
45	15	15	-	-	-	
46	28	28	-	-	-	
47	29	29	-	27	-	
48	29	29	-	15	-	
49	29	29	-	9	-	
50	29	29	-	9	-	
51	29	29	-	28	-	
52	29	29	-	27	-	
53	29	29	-	15	-	
54	29	29	-	27	-	
55	29	29	-	15	-	
56	29	29	-	27	-	

TABLE 26 (Continued)

Generating Point Number	Wastes Should be Shipped to the Following Site Numbers				
	Schedule One	Schedule Two	Schedule Three	Schedule Four	Schedule Five
57	15	15	-	-	-
58	16	15	-	-	-
59	16	15	-	-	-
60	16	15	-	-	-
61	16	15	-	-	-
62	17	17	-	-	-
63	17	17	-	-	-
64	18	18	-	-	-
65	19	19	-	-	-
66	19	19	-	-	-
67	20	20	-	-	-
68	21	21	-	-	-
69	21	21	-	-	-
70	23	23	-	-	-
71	22	22	-	-	-
72	43	43	44	-	-
73	33	33	-	-	-
74	44	44	-	-	-
75	38	38	-	-	-
76	38	38	-	-	-
77	43	43	38	-	-
78	39	39	-	-	-
79	39	39	-	-	-
80	40	40	-	-	-
81	41	41	-	-	-
82	41	41	-	-	-
83	59	59	-	-	-
84	42	42	-	-	-
85	42	42	-	-	-
86	42	42	-	-	-
87	42	42	-	-	-
88	46	46	-	-	-
89	48	48	-	-	-
90	48	48	-	-	-
91	50	50	-	-	-
92	50	50	-	-	-
93	51	51	-	-	-
94	59	59	-	-	-
95	57	57	-	-	-
96	57	57	-	-	-
97	57	57	-	-	-
98	57	57	-	-	-
99	52	52	-	-	-
100	55	55	-	-	-
101	52	52	-	-	-
102	3	3	-	-	-
103	58	58	-	-	-
104	61	61	-	-	-
105	43	43	36	-	-
106	36	36	-	-	-
107	36	36	-	-	-
108	36	36	-	-	-
109	36	36	-	-	-
110	36	36	-	-	-
111	36	36	-	-	-
112	36	36	-	-	-
113	36	36	-	-	-
114	36	36	-	-	-
115	43	43	44	-	-
116	43	43	44	-	-

Another implicit assumption was that the variable costs of disposing of solid wastes are linearly related to the amount of the solid wastes disposed of at the site. This cost is implicitly present in addition to the actual transfer of solid wastes. This assumption makes separate calculation unnecessary, inasmuch as the cost of disposal is added in the same proportion, irrespective of the allocation. The main reason the variable disposal cost cannot be treated as a function of the volume of the wastes coming to the site is that disposal costs cannot be determined until the allocation is known; and the allocation cannot be determined until the variable costs are known. This problem is not unsoluble; but in the present state of the art, no computationally feasible algorithm exists for a problem of this size.

The solid wastes management field is one area in which the technique developed herein could be effectively employed. The problem facing most communities today — both large and small — concerns not only the efficient use of existing disposal sites, but also an efficient transfer of solid wastes. The application of the type of algorithm developed in this part of the study can be helpful in developing an optimum solution toward selection of sites and transfer of solid wastes. Although capacity restriction on the sites does limit cost minimization somewhat and result in sub-optimum solutions, it would at least help in ranking the potential sites on the basis of costs. Different variations of this algorithm to alleviate the existing limitations are already under progress and will be reported in due course.

III. OPERATIONS RESEARCH IN SOLID WASTES

The comprehensive solid wastes generation and disposal model described in Chapter III of the First Annual Report [4] continued to provide the framework for the activities of the operations research group since the publication of the Second Annual Report [1]. During this time the emphasis shifted from models of optimal flow patterns of waste and optimal operating policies for disposal plants (short-planning horizon models) to the longer horizon problems of forcasting waste loads and optimal dosposal plant expansion strategies.

MODEL FOR FORECASTING WASTE LOADS

The basic rationale for the comprehensive solid wastes generation model mentioned in the preceding paragraph was derived from the Leontief Input-Output technique. The objective was to forecast a solid waste profile for an arbitrary geographical region and time period. The mode of attack was to augment a basic N by N interindustry Leontief model by M new indistries. Each new industry representing the service of disposing of waste of a particular type such as garbage, radioactive wastes, wrecked automobiles, etc. In this section of the present report, this approach is reviewed and an approximate procedure is developed to compensate for the present difficulty in obtaining adequate data on the waste disposal service industries themselves. The method is then applied to the nine-county San Francisco Bay region and forecasts for solid wastes generation in the region are proffered for a horizon of ten years.

The Leontief Model Augmented by the Solid Waste Disposal Service Industry

The Leontief Input-Output model is essentially a set of linear equations relating the input and output of the industrial sectors of a particular region. The basic equation equates the production of each industrial sector to the amount consumed by the consumption sector – the consumption sector being comprised of the household, government, capital investment, and net exports. The following is a representation of the N-sector industrial region:

$$x_i = \sum_{j=1}^{n} a_{ij}x_j + y_i; \; i=1,2,\ldots,N \qquad (1)$$

where

x_i = the value in millions of dollars of goods or services produced by industrial sector i in one year

a_{ij} = the value of goods or services of industrial sector i, in millions of dollars, required in the production of one million dollars of goods or services by industrial sector j (referred to as technological coefficients)

y_i = the final yearly demand of goods or services of type i, in millions of dollars, by the consumption sector

In matrix notation the following is obtained:

$$X = AX + Y \qquad (2)$$

or

$$(I-A)X = Y \tag{3}$$

where

I = the N by N identity matrix

A = an N by N technological coefficient matrix

X = an N-order column vector of total output production of goods or services

Y = an N-order column vector of final demands for goods or services.

Assuming the regional economy is viable, and therefore the inverse of (I-A) exists, the production vector, X, may be found by:

$$X = (I-A)^{-1}Y\ . \tag{4}$$

Thus, given a forecast of the final demand vector Y, the corresponding levels of production (X) of each of the N industrial sectors may be found.

These N equations may be augmented by the addition of M waste service disposal industries. Equation (1) becomes:

$$x_i = \sum_{j=1}^{n} a_{ij}x_j + \sum_{k=1}^{m} a_{i,n+k}x_{n+k} + y_i ; i=1,\ldots,N \tag{5}$$

where

x_{n+k} = the number of tons of waste disposal service of type k utilized in one year

$a_{i,n+k}$ = the value of goods or services of industrial sector i, in millions of dollars, required for the disposal of one ton of waste of type k.

Additionally M equations of type (5) are required to represent the waste disposal service industries themselves.

$$x_i = \sum_{j=1}^{n} a_{ij}x_j + \sum_{k=1}^{m} a_{i,n+k}x_{n+k}y_i ;\ i=N+1,\ldots,N+M \tag{6}$$

where

x_i = the number of tons of waste disposal service of type i performed in one year by waste disposal industry i

a_{ij} = the number of tons of waste disposal service of type i required in the production of one million dollars of goods or services by industrial sector j

$a_{i,n+k}$ = the number of tons of waste disposal service of type i required per ton of waste of type i,n+k serviced by waste disposal industry k

y_i = the final yearly demand of waste disposal in tons of waste of type i by the consumption sector.

The resulting N+M equations incorporate the interdependence of the M waste disposal industries of the region with its basic N industrial sectors. Of interest here are the last M industries, in particular the quantities $x_{N+1}, x_{N+2}, \ldots, x_{N+M}$, which represent the amount of waste processed by the M waste disposal industries. This then is equal to the amount of waste generated by the industrial and household sectors of the economy as reflected in (6), assuming that the government sector is absorbed in the N basic sectors.

A First Approximation of Total Wastes

As a first approximation it was decided to drop the intermediate input requirements of the waste service industries themselves. Thus, Equation (5) reverts to Equation (1), and the expressions for total waste (6) becomes:

$$x_i = \sum_{j=1}^{N} a_{ij} x_j + y_i; \qquad i=N+1, \ldots, N+M \tag{7}$$

It should be noted that the production levels for the N basic industries will be underestimated due to the exclusion of the required inputs to the waste industries themselves. This in conjunction with the delineation of the M terms in Equation (6) causes the forecast for total waste to be underestimated.

The procedure for finding the total waste levels, $x_i; i=N+1, \ldots, N+M$, from Equations (1) and (7) is as follows:

1. Estimate the final demands $y_i; i=1, \ldots, N$ for the N basic industries.
2. Find the corresponding production levels for these N industries from Equation (1).
3. Using these production levels as the x_j in (7), coupled with estimates of the waste services demanded by the household sectors, $y_i; i=N+1, \ldots, N+M$, and the waste coefficients, a_{ij}, compute the x_i for all the M waste disposal industries.

Ten-Year Forecast of Solid Wastes for the Nine-County San Francisco Bay Region

The total waste for the nine-county San Francisco Bay region was forecasted for the years 1970, 1974, 1978. The model was calibrated for the year 1966 from data obtained from the planning portion of this study. The method used in the forecast is that described in the preceding section. Due to difficulties obtaining data, all types of waste were treated as one, reducing the set of equations in (7) to one of the form,

$$x = \sum_{j=1}^{N} a_j x_j + y \tag{8}$$

where

x = the total quantity of solid waste of all types, in tons, produced in one year

a_j = tons of solid waste of all types per one million dollars of output by industry j

j = the total quantity of solid waste of all types, in tons, generated by the household sector of the economy.

TABLE 27

TOTAL WASTE BY SECTOR (28) – NINE-COUNTY SAN FRANCISCO BAY REGION, 1966

Sector	Description	Output Level	Waste Output	Waste Coeff.
j		Millions of Dollars x_j	Tons $a_j x_j$	Tons/Millions of Dollars a_j
1	Livestock & Livestock Products	$ 170.32	1,386,460.	$ 8,140.32
2	Other Agricultural Products	232.69	942,014.	4,048.36
3	Forestry & Fishery Products	1.59	0.	0.0
4	Agric., Forestry & Fishery Services	18.79	0.	0.0
5	Metal Mining	9.01	0.	0.0
6	Crude Petrol & Natural Gas	121.84	0.	0.0
7	Stone, Clay & Fertilizer Mining	3,676.22	0.	0.0
8	Construction & Demolition	957.45	981,061.	1,024.66
9	Ordnance & Accessories	3,680.55	15,053.	4.09
10	Food & Kindred Products	222.75	678,712.	3,046.97
11	Textiles & Apparel	122.26	5,751.	47.04
12	Lumber & Wood Products	376.83	95,211.	252.66
13	Furniture & Fixtures	492.93	115,329.	233.93
14	Paper & Allied Products	653.72	131,280.	200.82
15	Printing, Publishing & Allied	1,545.72	335,450.	217.02
16	Chemicals & Allied	75.22	115,312.	1,532.99
17	Petrol. Refining	19.39	151,692.	7,823.21
18	Rubber & Misc. Plastic	377.58	3,793.	10.05
19	Leather & Allied	459.11	165.	0.36
20	Stone, Glass & Clay	736.14	188,877.	256.58
21	Primary Metals	654.99	95,141.	145.26
22	Fabricated Metals	1,035.21	166,083.	160.43
23	Non Elec. Machinery	789.14	92,901.	117.73
24	Elec. Machinery	112.38	108,702.	967.27
25	Trans. Equipment	276.75	62,080.	224.32
26	Prof. & Scient. Instru.	2,030.95	10,060.	4.95
27	Misc. Manuf.	413.87	4,183.	10.11
28	Commercial & Public Facilities	$15,796.63	4,377,376.	$ 277.11

TABLE 28

AGGREGATED DEMAND VECTORS FOR NINE-COUNTY SAN FRANCISCO BAY REGION[a]

Sector	Y_{1966}	Y_{1970}	Y_{1974}	Y_{1978}
1	68.55	82.26	98.71	118.45
2	119.58	143.50	172.20	206.63
3	.22	.26	.32	.38
4	3.46	4.15	4.98	5.98
5	2.17	2.60	3.12	3.75
6	.08	.10	.12	.14
7	3,525.41	4,230.49	5,076.59	6,091.91
8	825.19	990.49	1,188.59	1,426.31
9	3,517.35	4,220.82	5,064.98	6,077.98
10	214.29	257.15	308.58	370.29
11	93.43	112.12	134.54	161.45
12	103.70	124.44	149.33	179.19
13	458.10	549.72	659.66	791.60
14	44.83	53.80	64.56	77.47
15	1,206.97	1,448.36	1,738.04	2,085.64
16	28.71	34.45	41.34	49.61
17	10.76	12.92	15.49	18.59
18	66.78	80.14	96.16	111.39
19	334.33	401.19	481.43	577.72
20	269.21	323.05	387.66	465.19
21	16.54	19.85	23.82	28.58
22	494.91	595.89	712.67	855.20
23	168.90	202.68	243.22	291.85
24	47.86	57.43	68.92	82.70
25	133.27	159.92	191.91	230.29
26	1,695.31	2,034.37	2,441.25	2,929.50
27	324.12	388.94	466.73	560.08
28	12,575.76	15,090.91	18,109.09	21,730.91

[a] 20% growth per four-year period.

No account was taken for technological change either in the technological coefficients of the N basic industries or in the waste coefficients (a_j). The technological coefficients (a_{ij}) used in Equation (1) were obtained from the multiregional input-output study conducted by the Economic Evaluation of Water Project at the Sanitary Engineering Research Laboratory, University of California, Berkeley. This was in the form of a 38 x 38 sector input-output table of technological coefficients (a_{ij}). This matrix was aggregated into a 28 x 28 sector matrix of coefficients. The sector descriptions may be found in column 2 of Table 27. Using the final demand vector for the 28 basic sectors (shown in column 2 of Table 28) for the year 1966, the vector of production levels, X, was computed (shown in column 3 of Table 27). The waste output for the base year, 1966, for each of the 28 industries was based on studies by the planning and economics team, and are tabulated in column 4 of Table 27. The waste coefficients required in Equation (8) are tabulated in column 5 of Table 27 and were obtained by dividing the elements of column 4 by those of column 5.

The total waste produced by the household sector, y, was estimated from the per family waste coefficients obtained from the city planning study. These are:

$$h_s = 1.43 \text{ tons/single-family unit}$$

$$h_m = 0.66 \text{ tons/multiple-family unit.}$$

The housing forecast for the nine-county San Francisco Bay region obtained from the BASS Study is tabulated in Table 29. The data for the year 1966 were found by interpolation, and when multiplied by the per family waste coefficients, resulted in a value of $y = 1,800,000$. This amount is to be added to the total waste output for the 28 industrial sectors found at the bottom of Table 1 in column 4. The resulting forecast in tons of solid waste, utilizing Equation (8), is

$$x = 9,804,860 + 1,800,000 = 11,604,860$$

Using the same technological (a_{ij}), industrial waste (a_j), and household waste (h_s, h_m) coefficients, a forecast was obtained for the years 1970, 1974, and 1978. It was assumed that the gross regional product increased at a nominal rate of 4.65 percent and that this was reflected in the growth of the final demand for the region. The final demand vectors, Y_t, for the year t are shown in Table 28 and were obtained by the following relation for t equal to 1966 and n equal to 4, 8, and 12.

$$Y_t = (1+0.046)^n Y_{t+n}$$

The production vectors x_{1970}, x_{1974}, and x_{1978} given in Table 30 were computed from Equation (1). These values were in turn multiplied by the appropriate waste coefficients, found in column 5 of Table 27, to obtain the total waste output for the industrial part of the economy. The total waste generated by the household sector of the economy for each year of the forecast was obtained by multiplying the household growth data of Table 29 by the household waste coefficients. The total waste forecast is summarized in Table 31.

The effect of the growth of the economy on the household waste coefficients will be considered in future work. This will be done by relating gross regional product to average income of single- and multiple-family dwellings; and in turn, relating average income to household waste production. Regression techniques are currently being employed for this purpose.

Extensions and Refinements

The assumption that all elements of the final demand vectors will increase at the same rate as was made for convenience only. The assumption leads to a sequence of output forecasts and waste forecasts vectors that are multiples of the 1966 vectors. An obvious refinement is to forecast the growth of final demands

TABLE 29

HOUSEHOLD FORECAST FOR THE NINE-COUNTY SAN FRANCISCO BAY AREA

Year	1965	1970	1974	1978
Type of Housing				
Single-Family Dwelling	942,633	1,058,475	1,172,230	1,279,238
Multi-Family Dwelling	445,167	500,257	554,913	610,532
Waste of				
Single Dwellings (tons)	1,347,965	1,513,619	1,676,289	1,829,310
Multiple Dwellings (tons)	293,810	330,169	366,243	402,951
Total Household Waste (tons)	1,641,715	1,843,789	2,042,531	2,232,261

independently for each sector. Such a forecast may be constructed with the use of national trends as a starting point, and then making modifications based on forecasts of future exports from and imports into the region. For example, as more agricultural land is committed to uses other than agriculture, a corresponding increase in agricultural imports into the region would be expected. This example points out the close connection between the economic forecasting model developed in the preceding paragraphs and the land-use model described in the First Annual Report.

In attempting to evaluate the economic feasibilities of a waste management technology, the compositions of the waste is at least as important as total tonnage. Since a great deal is known about the composition of the waste generator by each economic sector, the composition of the total waste can be estimated. Furthermore, if changes in the mix of economic activity can be predicted, then the corresponding changes in composition can be estimated. The ability to predict the impact of future changes in the economic structure of the region on solid waste generation (both total tonnage and composition) is perhaps the most significant feature of this interindustry input-output model.

OPTIMAL STRATEGIES IN CAPACITY EXPANSION

The method of solid waste disposal most widely practiced in the United States today is the landfill method. The type of fill may range from the simple open dump to the truly sanitary landfill. In terms of efficiency with respect to volume reduction, the landfill method is the least efficient since only a limited amount of volume reduction is accomplished in the operation of a landfill. Following the same criterion, incineration becomes a far more efficient method than landfill. In addition to the significant reduction in volume accomplished through incineration, a biologically and chemically inactive residue or ash is produced.

TABLE 30

FORECASTED OUTPUT (DOLLARS) FOR THE NINE-COUNTY SAN FRANCISCO BAY AREA

Sector	1966	1970	1974	1978
1	170.31	204.38	245.25	294.29
2	232.67	279.21	335.06	402.05
3	1.60	1.92	2.31	2.76
4	19.78	22.53	27.04	32.45
5	9.00	10.80	12.95	15.55
6	121.85	146.23	175.47	210.56
7	3,676.22	1,149.19	1,379.03	1,654.84
8	957.44	1,149.19	1,379.03	1,654.84
9	3,680.55	4,416.66	5,299.99	6,359.99
10	222.73	267.28	320.73	383.87
11	122.26	146.72	176.05	211.27
12	376.82	452.20	542.64	651.16
13	492.94	591.53	709.83	851.81
14	653.75	784.50	941.41	1,129.68
15	1,545.74	1,854.89	2,225.87	2,671.04
16	75.24	90.29	108.34	130.02
17	19.39	23.28	27.92	33.50
18	377.59	453.11	543.72	652.47
19	459.06	550.86	661.03	793.25
20	736.12	833.36	1,060.03	1,272.04
21	654.95	785.96	943.16	1,131.78
22	1,035.21	1,242.28	1,490.74	1,788.88
23	789.13	946.96	1,136.36	1,363.61
24	112.38	134.85	161.83	194.19
25	276.77	332.12	398.55	478.26
26	2,030.98	2,437.18	2,924.62	3,509.54
27	413.83	496.59	595.91	715.10
28	15,796.60	18,955.95	22,747.14	27,296.57
Total	35,059.90	42,072.27	50,486.75	60,584.05

TABLE 31

WASTE FORECAST FOR NINE-COUNTY SAN FRANCISCO BAY AREA

Sector	1966	1970	1974	1978
1	1,386,399	1,663,684	1,996,405	2,395,649
2	941,945	1,130,353	1,356,425	1,627,664
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	981,050	1,117,529	1,413,037	1,695,646
9	15,053	18,063	21,676	26,011
10	678,649	814,386	977,263	1,172,697
11	6,750	6,901	8,281	9,937
12	95,207	114,254	137,105	164,524
13	115,314	138,377	166,052	199,264
14	131,285	157,544	189,053	226,863
15	335,454	402,544	483,055	579,664
16	115,343	138,410	166,091	199,313
17	151,692	182,094	218,403	262,100
18	3,793	4,551	5,462	6,554
19	164	197	237	285
20	188,870	226,650	271,980	326,375
21	95,135	114,165	136,998	164,397
22	166,082	199,303	239,165	286,997
23	92,902	111,483	133,780	160,534
24	108,702	130,441	156,533	187,836
25	62,084	74,500	89,402	107,282
26	10,060	12,072	14,486	17,383
27	4,182	4,019	6,022	7,227
28	4,377,367	5,252,850	6,303,419	7,564,103
Total Waste Industrial	10,062,493	12,075,378	14,490,340	17,388,315
Household	1,800,000	1,843,789	2,042,531	2,232,261
Forecast	11,862,494	13,919,168	16,532,871	19,620,576

Because incineration is gaining increasingly wider acceptance as the disposal method for at least the near future, it was the technology selected for consideration in this section of the report. The incinerator, as well as any other types of disposal facility, is faced with an increasing demand on its disposal capacity. The demands will increase until they exceed the capacity of existing facilities. Because of this inevitably increasing demand on incinerator capacity, the question becomes one of how much should an existing plant be increased; and whether or not they should be made operational such that, in a sense, they incur the minimum possible cost in meeting the disposal needs.

Cost Structure

The cost rate of processing wastes at an input rate P by an incinerator of size K ($K \geq P$) was assumed to be W,

where

$$W = \alpha K + \gamma + \left(\frac{\beta}{K} + \delta\right) P$$

This cost structure is commonly used in accounting practice, and contains a "variable" component which is directly proportional to the processing rate, and a "fixed" component which is independent of the processing rate. The concept of economy of scale implies that the variable costs will decrease as plant size increases; hence we assume the variable cost component is of the form $(\delta + \beta/K)P$. The fixed cost component, since it includes maintenance and the cost of the capital invested in the plant, will certainly increase as plant size increases. Thus we assume a fixed cost component of the form $\gamma + \alpha K$.

Values of the parameters α, β, γ, and δ were estimated by multiple regression analysis of data collected on the costs of operating incinerator plants. The results of the analysis are listed in Table 32. Since from a technological viewpoint, all the parameters have to be positive, the range for the parameters was assumed in subsequent work to be as listed in Table 33. Whenever possible, the high and low values in Table 33 were determined to be at the mean plus or minus standard error.

First Part of Analysis-Infinite Horizon

An infinite planning horizon was assumed for the first part of the analysis. Another assumption was that no lump sum cost is associated with the installation and startup of a plant; and if there should be such a cost, it could be pro-rated over time and included in the fixed-cost component with maintenance and upkeep costs. The latter alternative could be achieved in practice by floating a bond issue or other similar step. The capacity of a plant once installed was assumed to be nondepreciable and nondisposable. Time was taken as a continuous parameter and exponential discounting was applied.

Two situations were studied for each demand rate: 1) one in which there is an alternative, meeting all the demand for disposal capacity by installing incinerator capacity (e.g., long haul to distant landfill); and 2) one in which no such alternative exists. Parameters of interest were the optimal size of the installed plants. These were determined on a theoretical basis for a number of demand-rate situations, namely, constant future demand, linearly increasing future demand with the present demand at zero, and linearly increasing future demand with the present demand being positive.

Findings

The most important theoretical result was that for any nondecreasing demand rate, there exists between any two build points (when additional plant capacities are installed) a regeneration point at which the demand rate equals the cumulative capacity. This result is comparable to that obtained in the simple back-order model in inventory theory in which all positive or all negative inventory levels are nonoptimal.

TABLE 32

RESULTS OF MULTIPLE REGRESSION ANALYSIS OF COST DATA ON INCINERATORS

Parameter	Units	Value	Standard Error	Student t	Significance Level	Beta Coefficient
γ	$/day	-135.90				
α	$/ton	1,308	0.7499	1.74414	0.10472	0.60857
β	$/day	317.88	786.66	0.39804	0.69706	0.23097
δ	$/ton	0.7732	1.9426	0.40410	0.69271	0.13591

TABLE 33

RANGE OF PARAMETERS FOR ANALYSIS OF INCINERATOR COSTS

Parameter	Low	Mean	High
α	0.5581	1.308	2.0579
β	117.88	317.88	517.88
γ	0.0	100.0	200.0
δ	0.0	0.7732	2.7158

Inasmuch as most of the equations involving optimal quantities turned out to be implicit, and in order to obtain a greater insight into the nature of the optimal policy, numerical results were obtained by the use of a digital computer. Many different demand-rate situations were studied for different values of the parameters α, β, γ, and δ and alternative cost c.

The conditions and results of the analysis are summarized in Table 34. In the analysis, yearly interest rate was assumed to be 9% per year (hence, $1+r = 1.000236$ which represents the interest rate on a daily basis), and initial demand to be 1,200 tons/day. Moreover, $m/r = 750, 1{,}500, 2{,}250$, which correspond to a linear growth of 60, 120, and 180 tons/day/year, respectively and represents the increase in demand rate in a daily basis. The optimal capacity to be installed when the initial demand is zero is represented by K^*, and $W(K^*)$ is the cost rate associated with such an optimal policy. K_1^* represents the optimal size of the first plant installed when the initial demand is d ($d > 0$). Note that the second and subsequent plant sizes will be of capacity K^*. The cost rate associated with this optimal policy is represented by $W(K^*)$. T_{01}^* and T_{11}^* are the times (measured after a regeneration point) when the plants of size K^* and K_1^* should be installed.

From the analysis it can be seen that the following characteristics hold in general:

1. Capacity and cost values are more sensitive to α and β.

2. Optimal capacity values are not affected by δ.

3. The smaller the alternative cost, the longer the installation time, and the smaller the incurred cost.

4. The capacity installed increases with decreasing α, increasing β, and increasing γ.

The case of linear probabilistic demand-rate also was analyzed and was found to be only slightly more complicated than the deterministic demand case. Numerical techniques were resorted to in this case, to obtain a better insight into the nature of the results which were sought.

Second Part of Analysis – Finite Planning Horizon

The second part of the analysis was based on the assumption of a finite planning horizon. Time was treated as being discrete in that this planning horizon was assumed to consist of N periods, and that the decision to increase the plant capacity could be made only at the beginning of a period. The assumed plant model was slightly different here. It was as if a single plant existed, and all capacity expansions resulted in an increased capacity of this single plant. Demands were assumed to be deterministic, and as before, disposal of capacity was assumed to be prohibited. In the most general case it was assumed that it costs a fixed amount, x_2, to order a capacity increase of any size, and that an alternative to increasing the capacity of the plant exists which costs c per unit demand rate of disposal capacity.

It was shown that when the fixed cost to build was zero, the optimal policy had a very simple structure. The problem, then, is effectively reduced to a one-period planning horizon. Hence the decision to build or not build at the beginning of the period depends solely on the costs incurred during the period. It was also shown that it will always be optimal to add capacity at the beginning of a period to the demand level of the period and that alternative means are never used at all.

When the fixed cost to build, x_2, is positive and when the alternative does not exist (c is infinite), the optimal policy is simple but somewhat more tedious to calculate, as is indicated by the following discussion. If the decision is made

TABLE 34

NUMERICAL RESULTS OF OPTIMAL POLICY ANALYSIS

Units	Case	1	2	3	4	5	6	7	8	9	10	11	12	13	14
\$/ton	α	1.308	1.308	1.308	0.5581	2.0579	1.308	1.308	1.308	1.308	1.308	1.308	1.308	1.308	1.308
\$/day	β	317.88	317.88	317.88	317.88	317.88	117.88	517.88	317.88	317.88	317.88	317.88	317.88	317.88	317.88
\$/day	γ	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0	200.0	100.0	100.0	100.0	100.0	100.0
\$/ton	δ	0.773	0.773	0.773	0.773	0.773	0.773	0.773	0.773	0.773	0.0	2.7158	0.773	0.773	0.773
\$/ton	c	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	5.0	10.0	20.0
tons/day^2	m/k	1,500	750	2,250	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500
tons/day	K^*	886.55	609.59	1,115.9	1,337.9	743.99	660.83	1,040.9	803.39	981.59	886.55	886.55	1,088.0	979.39	932.81
\$/day	$W(K^*)$	4,520.0	2,583.6	6,368.8	2,950.6	5,971.5	4,133.5	4,826.4	4,287.1	4,735.1	3,360.5	7,434.2	4,200.2	4,382.7	4,456.0
tons/day	d	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200
tons/day	K_1^*	2,063.9	1,761.5	2,279.9	2,495.9	9,409.1	6,645.1	7,401.6	1,977.5	2,063.9	2,063.9	2,063.9	1,920.0	1,992.0	2,063.9
\$/day	$W_1(K_1^*)$	7,061.8	5,147.1	8,900.6	4,598.3	9,409.1	6,645.1	7,401.6	6,826.6	7,282.8	4,974.7	12,307.0	6,873.3	6,983.3	7,025.9
day	t_{oi}^*	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1,093.4	438.22	197.46
day	t_{1i}^*	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 35

OPTIMAL POLICY FOR A 200-PERIOD PROBLEM WITH DEMAND INITIALLY 1200 TONS/DAY TO INCREASING LINEARLY AT 10 TONS/DAY/MONTH

Capacity Increased at Beginning of Period	Size of Capacity Increase tons/day	Cumulative Capacity Increased to Level tons/day
1	1,330.0	1,330.0
15	140.0	1,470.0
29	140.0	1,610.0
43	140.0	1,750.0
57	140.0	1,890.0
71	130.0	2,020.0
84	130.0	2,150.0
97	130.0	2,150.0
110	130.0	2,410.0
123	130.0	2,540.0
136	130.0	2,670.0
149	130.0	2,800.0
162	130.0	2,930.0
175	130.0	3,060.0
188	130.0	3,190.0

to build some capacity at the beginning of the period, then the optimal level to which building takes place can be any of the demand levels faced in the future. Hence for a given period, only a finite number of choices can be made. A problem of this sort can be solved by using the shortest path approach in a network. However, that approach was abandoned because it required too many calculations to obtain the optimal policy. To obtain numerical results, the problem was formulated as a dynamic programming problem. Special mathematical structuring of the problem helped reduce the number of calculations required to only about 1/5 of the original value and the scheme now is quite computationally efficient.

The optimal policy was calculated for a 200-period problem (each period corresponding to a month) in which the demand initially was 1,200 tons/day and alternative costs were infinite; a) When demand increases linearly at the rate of 10 tons/day per month (120 tons/day per year or 10% a year) the optimal policy is as shown in Table 35. The demand for period j+1 can be expressed as

$$d_{j+1} = d_j + 10.0 \quad \text{with } d_1 = 1,200.0 \quad .$$

The parameter values were taken as:

$$\alpha = 1.308, \; \beta = 317.88, \; \gamma_1 = 100.0, \; \delta = 0.773, \; \gamma_2 = 1,000.0 \quad .$$

b) When demand increases geometrically at the rate of 0.833% a month (which roughly corresponds to 10% a year), the optimal policy is shown in Table 36. The demand for period j+1 can be expressed as

$$d_{j+1} = d_j \cdot 1.00833 \text{ with } d_1 = 1,200.0 \quad .$$

TABLE 36

OPTIMAL POLICY WHEN THE DEMAND INITIALLY IS 1200 TONS PER DAY AND INCREASES GEOMETRICALLY AT 0.833% PER MONTH

Capacity Increased at Beginning of Period	Size of Capacity Increase tons/day	Cumulative Capacity Increased to Level tons/day
1	1,325.66	1,325.66
14	138.81	1,464.47
26	153.35	1,617.82
38	154.63	1,772.45
49	169.42	1,941.87
60	168.03	2,109.90
70	182.57	2,292.47
80	177.78	2,470.25
89	191.56	2,661.81
98	182.72	2,844.53
106	195.26	3,039.79
114	208.66	3,248.45
122	222.99	3,471.44
130	207.63	3,679.07
137	220.00	3,899.12
144	233.22	4,132.34
151	247.16	4,379.50
158	261.95	4,641.45
165	236.96	4,878.41
171	249.06	5,127.47
177	261.77	5,389.24
183	275.14	5,664.38
189	289.19	5,953.57
195	303.95	6,257.52

The parameter values were taken as:

$$\alpha = 1.308,\ \beta = 317.88,\ \gamma_1 = 100.0,\ \delta = 0.773,\ \gamma_2 = 1,000.0$$

The analysis showed that the frequency and the optimal size of capacity increase depends much more strongly on the demand values and the rate of increase in the near future than on the demand values in the distant future. This certainly is a good omen as far as a real-life situation is concerned.

For the most general case, that is, when γ_2 is positive, and c finite but positive, it was shown that the simple structure of the optimal policy no longer holds, i.e., that the optimal policy corresponds to interior point solutions. Although the shortest path method and dynamic programming approach can be used here to obtain the optimal policy, it requires a far greater number of calculations than in the previous cases. The required number of calculations was reduced considerably by developing an upper bound to which the capacity can be increased for any periods and a lower bound on existing capacity which triggers a build for that period. A new approach was developed in which attention was focused on the last period at which the capacity was increased. The latter approach was coded because it proved to be the most efficient. Thus optimal policies can be found for a finite planning horizon and given demand sequence.

General theoretical questions concerning the first part of the analysis were investigated. Thus, a study was made of the nature of the demand function which would give rise to nondecreasing or nonincreasing capacity installations. Some sufficiency conditions for the demand function for nonincreasing capacity installations were devised. However, this analysis proved to be quite weak and of little practical use. A Markov renewal approach also was made to arrive at generalized cost functions for maintenance and for upkeep costs and variable processing costs so as to obtain stronger sufficiency conditions. However, again the derived conditions were more of theoretical interest than of practical value.

Details of the mathematical derivations that support the results described in the preceding paragraphs will be given in the soon-to-be published, University of California, report "Optimal Strategies in Plant Expansion," by A. K. Nigam.

IV. ANAEROBIC DIGESTION

INTRODUCTION

The application of anaerobic digestion to materials other than sewage sludge alone is not a new concept in municipal wastes management. Numerous communities have practiced some degree of dual disposal of garbage and sewage for many years as a result of the widespread use of the home garbage grinder. This has resulted in a significant reduction of the garbage fraction of domestic solid wastes without disruption of the sewage treatment process. The concept that other organic fractions of the total refuse of a community might also be reduced in volume and stabilized in this manner is, therefore, but one step beyond current practice.

An integral and attractive aspect of this concept is the use of hydraulic transport. Generally, existing sewer systems would be used with the refuse being ground into the sewers at points of origin or at central grinding stations. Certain materials such as metals, brick, and other high density inert materials would have to be excluded, but the greater part of domestic, light commercial, and agricultural wastes could be transported in this manner. Experiments conducted by the Los Angeles County Sanitation Districts demonstrated the efficacy of refuse transport in sewers. The major difficulty encountered in the Los Angeles experiments resulted from the fact that the sewage treatment plant was not designed to accept the added burden of solids reaching it. As one would expect, if refuse were to be transported by way of sewers, existing treatment facilities would have to be expanded in terms of grit removal chambers, primary sedimentation tanks, and increased digester capacity to cope with the higher solids loading.

Combining solid and liquid wastes to facilitate waste disposal is a possibility that has several advantages. Sorted ground refuse can be transported from central grinding stations through existing sewer systems, thus reducing hauling costs. At the treatment plant the combined solids can be stabilized and reduced in volume by conventional anaerobic digestion. The dewatered residue can be used as a soil conditioner or as a cover for landfills.

OBJECTIVES

Laboratory studies on the anaerobic digestion of solid wastes were directed toward the following specific objectives:

1. To determine the efficiency achieved by the process in terms of stabilization of volatile matter and weight reduction with respect to each major component of organic solid wastes.

2. To assess the effect on the digestion process exerted by a given waste material, i.e., possible retardation or toxic effects.

3. To investigate the feasibility of digestion of organic solid wastes and sewage sludge in terms of per capita generation of wastes.

4. To determine proper loading proportions in terms of C:N ratio as applied either to the digestion of mixed refuse or to the digestion of selected components of solid wastes with sewage sludge.

5. To determine maximum permissible hydraulic and organic loading rates in dual disposal systems.

6. To investigate the utilization of animal manures as a nitrogen source in solid waste digestion, and to determine the reduction in the bulk of the manures accomplished by this process.

7. To consider the benefits of grinding to sewers for solid waste transport regardless of whether there is the added benefit of solids reduction by an accompanying digestion process.

8. To assess the economic feasibility of digestion of garbage only and of the digestion of total urban refuse with sewage sludge.

THE INVESTIGATION

Principles Involved

Studies to date were confined to the use of laboratory-scale digesters of 1-gal capacity. The apparatus and analytical methods which were employed were described in the First and Second Annual Reports. During the period encompassed by the present report, several new techniques were adopted to evaluate the efficiency of digestion. These include a study of the kinetics of cellulose digestion, methods for determining the efficiency of the digestion of the solid waste portion of the feed, and of the efficiency of the destruction of the cellulose in the solid waste portion of the feed. A description of these techniques follows.

Kinetics of Solid Waste Digestion. The Michaelis-Menten kinetic model has been employed by many investigators and has been found suitable for describing anaerobic fermentation systems such as domestic sludge digestion. Hence, it was used in the present study to arrive at a quantitative kinetic description of the process as applied to cellulose. Since fundamental information regarding the kinetics of refuse digestion permits an evaluation of operational parameters, the equations which follow were used to determine kinetic constants for the particular system reported herein.

To obtain a process materials balance, two factors must be considered—substrate removal and cells produced. In a continuously mixed reactor at steady state, the substrate removal rate, q, may be expressed as the mass of substrate removal from the waste stream per unit of mass of active organisms per unit of time, i.e.,

$$q = \frac{S_0 - S_1}{X_1 \theta} \qquad (9)$$

in which

S_0 = influent substrate concentration, mg/ℓ

S_1 = digester substrate concentration, mg/ℓ

X_1 = cell concentration in the digester, mg/ℓ

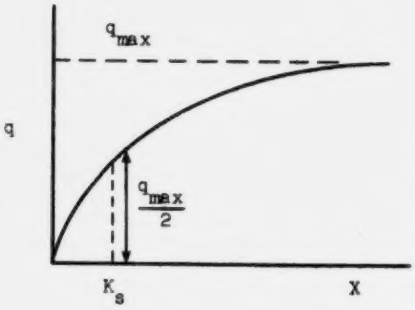
θ = hydraulic residence time, days

In laboratory digester studies involving mixed refuse, the values required to solve for q in Equation (9) were measured by assuming that the substrate concentration equals the cellulose concentration, and by estimating cell concentration on the basis of the organic nitrogen concentration. Although other methods of estimating cell concentration such as volatile suspended solids and dehydrogenase activity were tried, they proved unsuitable for use in this study because only very low correlation coefficients were obtained.

The maximum digestion rate of cellulose may be estimated by the Michaelis-Menten enzyme catalyzed reaction model, which expresses the relationship between the rate of substrate utilization and the concentration of substrate. The advantages of the Michaelis-Menten model are that at low concentrations it is first order (continuous function) and it approaches zero at high substrate concentrations.

it is expressed as:

$$q = \frac{q_{max} \cdot S}{K_s + S} \tag{10}$$



where

q = substrate removal rate (digestion rate of cellulose)

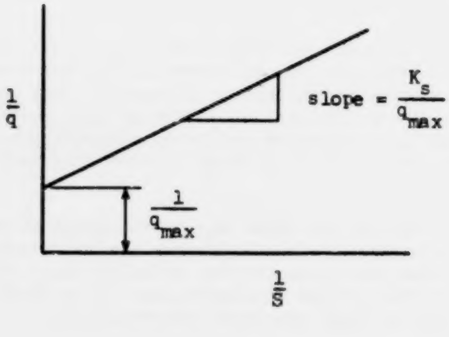
S = cellulose concentration in digester, mg/ℓ

q_{max} = an assumed constant denoting maximum hydrolysis rate of cellulose at infinite cellulose concentration

K_s = Michaelis-Menten constant, equal to the cellulose concentration at one-half q_{max}.

The straight line form of the above plot provides a graphical solution of the constants q_{max} and K_s.

$$\frac{1}{q} = \frac{K_s}{q_{max}} \cdot \frac{1}{S} + \frac{1}{q_{max}} \quad . \tag{11}$$



The substrate removal rate, q, can be transformed to cell growth rate, μ, by multiplying q by the yield coefficient, Y, as follows:

$$q\,Y = \mu \qquad (12)$$

where

Y = is assumed to be constant in this study and yield in mass of cells produced per mass of substrate removed

μ = specific growth rate $\left(\frac{1}{X}\ \frac{dX}{dt} = \mu\right)$.

Maximum growth rate may be determined from Monod's classic growth equation relating organism growth to substrate concentration, in mathematical form identical with the Michaelis-Menten equation (Equation 10).

$$\mu = \frac{\mu_{max} \cdot S}{K_s + S} \qquad (13)$$

where

μ = specific growth rate, day^{-1}

μ_{max} = an assumed constant denoting maximum specific growth rate at infinite substrate concentration, day^{-1}

S = substrate concentration, mg/ℓ

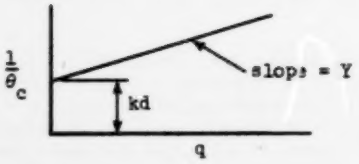
K_s = substrate concentration at $\frac{1}{2}\ \mu_{max}$, mg/ℓ .

Assuming there are no incoming cells in the influent to the continuous flow noncell digester recycling refuse, then the mean cell residence time, θ_c, equals the hydraulic residence time, θ. The net growth rate equals the specific growth rate, μ, minus decay rate. From Equation (12), μ = Yq, it is apparent that the net growth rate may be expressed as follows:

$$\frac{1}{\theta_c} = Yq - kd \qquad (14)$$

or

$$\frac{1}{\theta} = Yq - kd$$



where

θ_c = mean cell residence time, days

$\frac{1}{\theta_c}$ = net growth rate, day^{-1}

kd = decay rate, day^{-1}

As expressed in Equations (10) and (14), the cell washout time or critical residence time, $1/\theta_w$, is calculated from the constants Y, q_{max}, and kd. It is hydraulically the minimum residence time at which a stable cell population can be maintained. It is represented as:

$$\frac{1}{\theta_w} = Y\, q_{max} - kd \quad . \tag{15}$$

The cell doubling time, G, may be calculated from the maximum growth rate, μ_{max}.

$$G = \frac{\ln 2}{\mu_{max}} \quad . \tag{16}$$

Methods. Two new methods for calculating efficiency were adopted to delineate the fate of the added solid waste portion of the feed from the total digestion results. The first was concerned with the destruction of the solid wastes in the feed; and the second, with the destruction of the cellulose in the solid wastes.

The efficiency of solid wastes destruction was determined as follows: For a mixture of sludge plus an added solid waste, the digestion efficiency of the solid waste component may be calculated by comparing the efficiency of a raw sewage sludge digester (control) to the test digester on the basis of cubic feet of gas produced per pound of volatile solids added.

$$\text{Percent destruction} = \frac{\%\text{ solid waste in feed} - \text{efficiency loss, }\% \times 100}{\%\text{ solid waste in feed}}$$

$$\text{Where the efficiency loss} = \frac{\text{control, cu ft/lb} - \text{test, cu ft/lb}}{\text{control, cu ft/lb}} \times 100 \quad .$$

Efficiency of destruction of cellulose was determined as follows: Based on known inputs of cellulose from the sewage sludge and from the solid wastes, and assuming that the average cellulose destruction in the control is at the same rate as in the sludge portion of the test digester, then the residual cellulose attributable to undigested sludge may be calculated. Subtracting this value from that for total residual cellulose yields the value for the quantity of undigested cellulose in the residue of the solid waste. The following is an example of the calculations:

> Given the following conditions: Feed mix – 10% newspaper, 90% sludge; loading – 0.077 lb/cu ft digester = 3.70 g VS/day; sludge cellulose at 100% = 1.736 g/day input; newspaper cellulose content – 88.5%; average cellulose destruction control = 87.9% and residual cellulose in the test digester = 0.336 g; then the input of cellulose per day from sludge is 1.736 x 0.90 = 1.562 g; and from newspapers 3.70 x 0.10 x 0.885 = 0.327 g.

Since the average cellulose destruction in the control equals 87.9%, then the cellulose residual attributable to sludge input in the test digester is:

1.562 x (100 - 0.879) = 0.189 g

Total residual cellulose = 0.336 g

Sludge residual cellulose (-) 0.189 g

Newspaper residual cellulose = 0.147 g

and newspaper cellulose destruction = $\frac{0.327 - 0.147}{0.327} \times 100\% = 55\%$.

General Materials and Methods

Preparation of Raw Materials. With the exception of newspaper, each solid waste material was prepared in a sufficient quantity to satisfy the requirements of all studies reported herein. The newspapers were prepared in two batches.

A synthetic refuse was used in some of the experiments. It consisted of a mixture of grass clippings, green garbage, wood (white fir), Kraft paper, and newsprint. The grass clippings, garbage, and wood were mixed and stored separately from the paper until the time of the experiments. The grass, garbage, and wood mixture was 48.3% green garbage (air-dry total solids), 34.1% grass clippings (air-dry total solids), and 17.5% white fir (air-dry total solids). The computed moisture content was 10.2%; computed volatile solids, 82.3%; cellulose content, 47.9% (air-dry); total carbon, 35.8% (air-dry); and total nitrogen, 2.4% (air-dry). The mixture was stored at 2°C until it was used.

The Kraft paper was hammermilled to a fine powder. The moisture content of the powder was 6%; volatile solids on an air-dried basis were 93.6% (99.6% on dry weight basis); the fixed solids, 0.4% (dry weight); cellulose, 97.3% (dry weight); total carbon, 38.1% (air-dry); and total nitrogen, 0%. The newspaper also was hammermilled to a fine powder. Its moisture content was 7%; volatile solids, 100% (dry weight); cellulose, 97.3% (dry weight); total carbon, 38.6% (air-dry); and total nitrogen 0.019% (air-dry).

Experiments also were conducted in which each of the components of the "synthetic" refuse was studied separately. The grass clippings were air-dried and then were ground to a fine powder in a Wiley mill. The powder was stored in polyethylene bags at -2° C. The moisture content of the powder was 24.8%; the volatile solids, 87% (dry weight); and the cellulose, 60.3% (dry weight). The green garbage was obtained as vegetable trimmings from a local supermarket. It consisted of about 80% lettuce, 10% cabbage, and the remainder being corn husks, parsley, and miscellaneous greens. The material was dried to less than 1% moisture, and then was hammermilled. The powder was stored in polyethylene bags at 2°C. The moisture content of the powder was less than 1%; volatile solids, 91.2% (dry weight); and cellulose content, 40.8% (dry weight).

The wood (white fir) was obtained in the form of chips. The chips were ground to a fine powder in a Wiley mill. The powder was stored in sealed glass containers at room temperature. The moisture content of the powder was 9.3%; its volatile solids, 99.5% (dry weight); and its cellulose, 74.4% (dry weight).

When newsprint was studied on an individual basis, a different batch from that used in the "synthetic" refuse served as the substrate, it was prepared by blending with water in a Waring blender, then air drying overnight, and storing the moisture material is polyethylene bags at 2°C. This material served as substrate in the runs with sewage sludge and chicken manure as the only other components of the feed mixture. The shredded newspaper contained on a dry weight basis 88.5% cellulose, 97.1% volatile solids, 40.6% total carbon, 0.05% total nitrogen, and its moisture content after preparation was 70.8%.

Animal Manures. Chicken manure and steer manure were investigated individually and in combination with sewage sludge and solid waste materials. Chicken manure had been used in previous studies as a source of nitrogen in digesting nitrogen-deficient wastes. The nitrogen content of the manure was 3.2% (dry weight); carbon 23.4% (dry weight); moisture content 9.8%; volatile solids content, 56.2%; and inorganic material, 43.8% (dry weight).

Steer manure was obtained from a commercially packaged fertilizer product containing no additives. Its moisture content was 45.7%; volatile solids, 68.5% (dry weight); total nitrogen, 1.35% (dry weight); organic nitrogen, 1.22% (dry weight); NH_3-N, 0.13% (dry weight); and total carbon, 34.1% (dry weight).

FIRST EXPERIMENTAL SERIES – DIGESTION OF NEWSPAPER

The fact that paper constitutes about one-half of domestic solid wastes and nearly three-fourths of organic solid wastes demonstrates the significance of determining the degradability of this material in disposal processes. Kraft paper, which is wood-free, was shown in previous studies to be readily destroyed by anaerobic digestion (over 90%). However, newspaper contains about 75% ground wood pulp, and thus may be expected to be much more resistant to biodegradation. It is, therefore, important to defferentiate between the quantity of waste paper that is essentially wood-free and that amount which contains wood stock. Recent figures indicate that U. S. consumption of newsprint to be about 9 million tons annually, which is almost 20% of the total 50 million tons of paper consumed. This compares to about 10 million tons of Kraft apper consumption. The remaining material consists of mixed grades, some of which may be classified as wood-free and others containing wood stock. It is difficult to classify the latter material on the basis of wood content; but based on recent figures an estimated 55% of it is wood-free.

Salvage of waste paper currently is approximately 20% of that produced, or about 10 million tons per year. It is estimated from figures on secondary fiber consumption supplied by the American Paper Institute that the ratio of wood to wood-free stock in the salvaged paper is about 1:1. The paper industry would like to increase salvage and conserve paper stock, but current collection practices tend to soil most of the waste paper through contact with garbage. The Berkeley composition study [4] showed that of the waste paper arriving at the disposal site 80% was soiled. This soiled paper constituted 34.7% of the total domestic wastes (wet basis), and clean paper comprised 9.9% of the total (wet basis).

Clean paper separated from the main stream of solid wastes would not be recommended for a conversion process such as anaerobic digestion even if there were no salvage market, since paper is a compact material and the reduction in bulk afforded by digestion or any other process probably would not be worth the effort. Furthermore, clean paper is inoffensive and may be readily disposed of in any manner without creating nuisances.

From the above considerations it seems likely that domestic solid wastes will continue to contain upwards of 50% waste paper intermingled with other wastes. Disposal practices must therefore cope with this heterogenous mass of material, including the 20% to 25% of paper from wood stock such as newspaper. Because other components of solid waste, such as garbage and garden debris, contain a considerable amount of moisture compared to paper, the paper content represents about 75% of the total weight, in terms of quantity of dry-weight material comprising the organic portion of municipal refuse. It thus becomes apparent that the capability of a given process for breaking down paper is of paramount importance in assessing the relative merits of that process as a disposal technique.

Procedure

One digester (unit 1) served as the control and received only sewage sludge. A second digester (unit 2) received sewage sludge and newspaper. For unit 2 the newspaper portion constituted 10% of the volatile solids loading during the first 40 days of the run. During the next 80 days, digester 2 received a newspaper loading equal to 20% of the total input. In the final period (88 days), the loading to the two digesters was 30% newspaper. The cultures in units 1 and 2 were mixed throughout the experimental period by timer-operated magnetic stirrers on a schedule of 1.5 minutes each hour. A third digester (unit 12) was not mixed. It received a mixture of 50% newspaper and 50% chicken manure for a period Of 98 days. The culture volume in the three digesters was 3 liters per digester. The nominal detention period of the cultures was 30 days, and the loading was 0.077 lb volatile solids/cu ft digester capacity.

Results

The efficiency of the three digesters is shown in Table 37 in terms of gas production based on volatile solids added and volatile solids destroyed. For some reason, the control (unit 1) decreased in efficiency as the experiment progressed. However, the values shown in the Table are within the normal range of fluctuations for these parameters. In order to assess the efficiency of newspaper digestion for comparison with that of digestion, the impact of the added waste material must be calculated. This may be done by taking the loss in efficiency resulting from the percentage of waste material present in the feed. Such a procedure is relevant only to unit 2 which was fed sludge as well as paper, and may therefore be compared to the sludge control. On the basis of added volatile solids, the data shown in Table 38 can be obtained on the basis of the average values listed in Table 37.

The destruction of newspaper during the initial period apparently was only 8% of that introduced. However, with newspaper constituting only 10% of the added material, experimental errors are magnified by the calculations. More accurate assessments were possible at the 20% newspaper loading. At this loading, the calculated destruction of newspaper proved to be 53.5% [illegible]t 30% newspaper loading, the percent destruction was 44.3%. The average of these two values, namely 48.9%, agrees very closely with results in later experiments in which cellulose destruction averaged 47.0%.

Efficiency in terms of gas produced per unit of volatile solids added rather than per unit of volatile solids destroyed is much more meaningful in solid waste digestion experiments. If an added waste material is not destroyed at all, the efficiency in terms of gas production per volatile solids destroyed is not affected in the slightest. The digester fed paper and manure (unit 12) is an example of this discrepancy. On the basis of volatile solids added, gas production was 4.1 cu ft per lb of volatile solids; whereas in terms of volatile solids destroyed, it was 12.4 lb per lb volatile solids. Obviously the digestion efficiency of the culture receiving a newspaper-chicken manure mixture was quite poor, but on a destroyed basis this would not be apparent. For unit 2, the loss in efficiency on the basis of gas produced per pound of volatile solids destroyed was only about 10% when compared to the control. This leads to the erroneous conclusion that the digestion of newspaper proceeded almost as efficiently as that of sewage sludge.

A comprehensive picture of the valid parameters of efficiency in terms of gas production per unit of volatile solids added is shown in Figure 2. The poor overall efficiency of unit 12 becomes evident in the figure. The magnitude of decrease in efficiency as the newspaper loading to unit 2 is increased may be observed. Volatile solids reduction was more affected than was total solids reduction. Cellulose destruction decreased to an even greater extent. The average cellulose destruction in unit 2 during each period is shown in Table 39 together with the calculated destruction of newspaper-derived cellulose.

A weighted average of 47.0% newspaper cellulose destruction was obtained on the basis of the number of determinations run (at 55.0%, n = 5; 49.6%, n = 11; 41.7%, n = 13). The destruction of the cellulose in newsprint was about one-half that of Kraft paper due to the resistance of lignin to anaerobic decomposition.

No serious adverse effects on acid-base parameters were noted, as is evident from Figure 3 in which pH, volatile acid concentration, and alkalinity are plotted. As observed in other experiments, decreases of the proportion of sludge in the feed mixture resulted in a lower alkalinity and pH, although the volatile acid content remained stable. Despite the poor digestion efficiency of the culture in unit 12 (newspaper and manure) the culture was in quite good condition.

TABLE 37

GAS PRODUCTION PER POUND OF VOLATILE SOLIDS INTRODUCED IN THE DIGESTER RECEIVING NEWSPAPER AND SEWAGE SLUDGE

Day	Unit 1 (100% Sludge)		Unit 2 (10% NP[a] 90% Sludge)		Unit 12 (50% NP 50% CM[b])	
	Added	Destr.	Added	Destr.	Added	Destr.
12	12.2	19.0	10.6	16.0		
15	10.5	16.3	9.4	14.4		
19	10.5	16.1	9.4	14.3		
22	10.0	16.0	9.7	15.2		
26	10.0	16.0	9.7	15.3		
33	11.2	17.0	10.0	15.9		
36	11.4	17.4	10.0	16.0		
40	11.4	17.8	10.0	15.8		
			(20% NP 80% Sludge)			
43	11.1	17.8	9.6	15.5		
47	11.1	18.1	9.6	15.8		
50	9.3	14.2	7.9	12.7		
54	9.3	14.7	7.9	12.9		
57	11.1	17.9	9.8	16.6		
61	11.1	17.2	9.8	16.0		
64	9.2	14.8	8.4	14.2		
68	9.2	14.3	8.4	14.5		
71	9.4	14.5	8.0	13.3		
75	9.4	19.5	8.0	19.0		
78	10.0	19.1	8.4	19.5		
82	10.0	18.5	8.4	18.0		
85	9.1	16.8	8.1	17.8		
92	9.1	16.0	7.6	15.8		
96	9.1	14.8	7.6	14.1		
99	10.2	16.6	8.9	16.9		
103	10.2	17.0	8.9	16.7		
106	9.5	15.9	7.8	13.0		
110	9.5	15.7	7.8	13.8	4.9	11.8
113	9.2	14.8	7.5	13.0	3.8	9.3
117	9.2	14.3	7.5	13.0	--	--
120	8.7	13.5	7.5	13.1	3.8	10.1
Day	Unit 1 (100% Sludge)		Unit 2 (30% NP 70% Sludge)		Unit 12 (50% NP 50% Sludge)	
	Added	Destr.	Added	Destr.	Added	Destr.
124	8.9	12.1	7.5	11.7	3.8	9.8
131	--	--	7.0	11.0	4.2	11.8
138	9.4	13.2	7.9	12.5	4.2	15.3
145	9.6	13.6	8.0	12.5	4.2	13.9
152	10.1	14.1	7.9	12.7	3.9	14.5
159	10.1	14.7	8.0	13.4	3.7	11.8
166	9.6	14.0	8.0	13.6	3.6	11.4
173	8.6	12.6	7.0	13.6	3.6	11.4
180	8.6	13.0	7.1	13.7	4.8	15.2
187	8.4	12.3	7.1	13.0	4.9	15.5
194	8.3	12.4	7.0	12.8	4.4	14.5
201	8.6	12.9	7.1	13.9	4.0	12.0
208	8.5	12.6	7.6	14.3	4.0	12.6
AVG.						
12-40	10.9	17.0	9.9	15.4		
43-120	9.7	16.2	8.8	15.2		
124-208	9.0	13.1	7.5	13.0		
110-208	9.0	13.3			4.1	12.4

[a] NP = Newspaper

[b] CM = Chicken Manure

TABLE 38

EFFICIENCY OF NEWSPAPER DIGESTION BASED ON COMPARISON WITH CONTROL (UNIT 1 - 100 PERCENT SLUDGE)

Efficiency	Unit	Unit 2 (Fed with Newspaper and Sludge Mixture)		
		10% NP, 90% SL	20% NP, 80% SL	30% NP, 70% SL
$\frac{\text{cu ft gas produced}}{\text{lb VS added}}$	1 2	10.9 9.9	9.7 8.8	9.0 7.5
Efficiency loss, %	2	9.2	9.3	16.7
Calculated newspaper destruction, %[a]	2	8.0	53.5	44.3

[a] Calculated Destruction, % = $\frac{\text{Waste \%} - \text{Efficiency Loss \%}}{\text{Waste \%}} \times 100$.

TABLE 39

DESTRUCTION OF NEWSPAPER CELLULOSE BASED ON COMPARISON WITH CONTROL

Parameter	Unit	Unit 2 (Fed Newspaper [NP] and Sludge Mixture [SL])		
		10% NP, 90% SL	20% NP, 80% SL	30% NP, 70% SL
Total Cellulose Destruction, %	1 2	87.9 82.8	81.7 73.3	79.9 63.0
Calculated Newspaper[a] Cellulose Destruction, %	2	55.0	49.6	41.7

[a] Calculations (see Materials and Methods section for sample calculation).

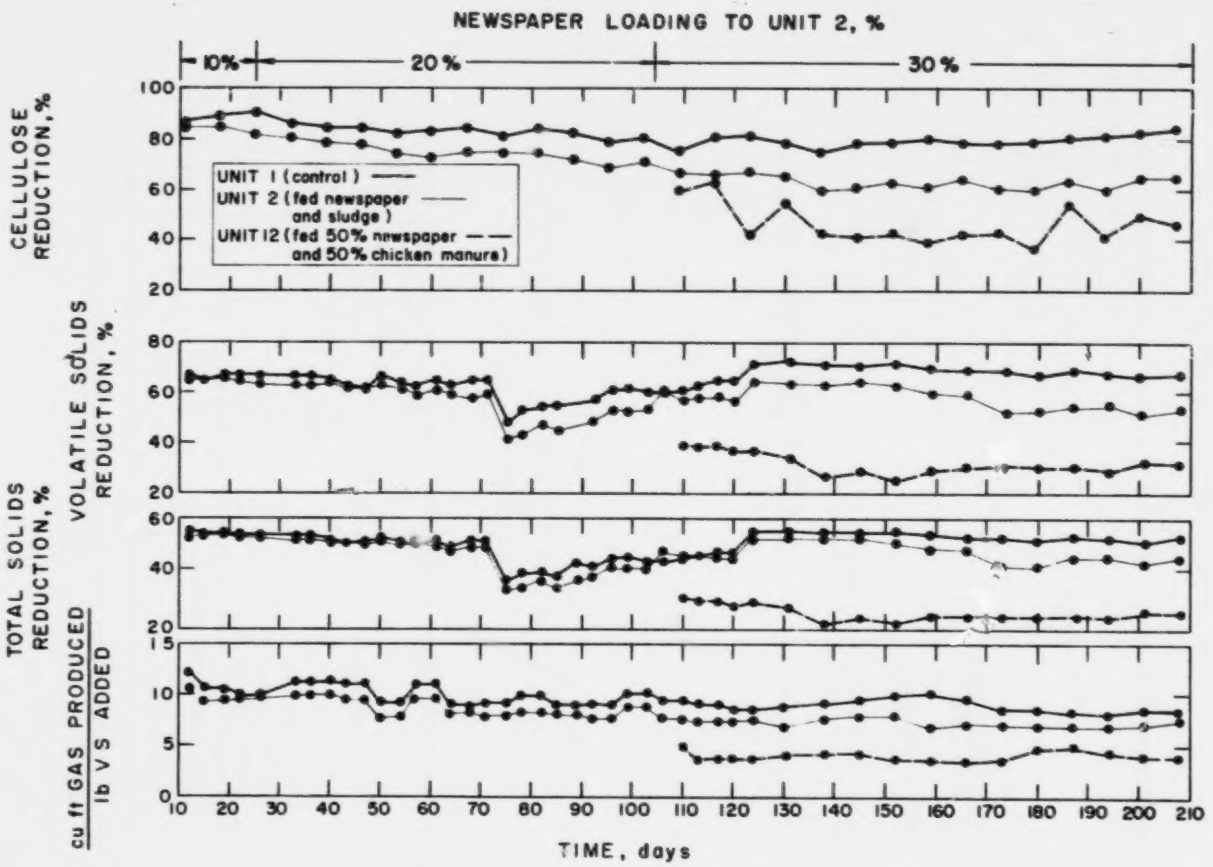


FIGURE 2. EFFICIENCY OF NEWSPAPER DIGESTION

SW 108

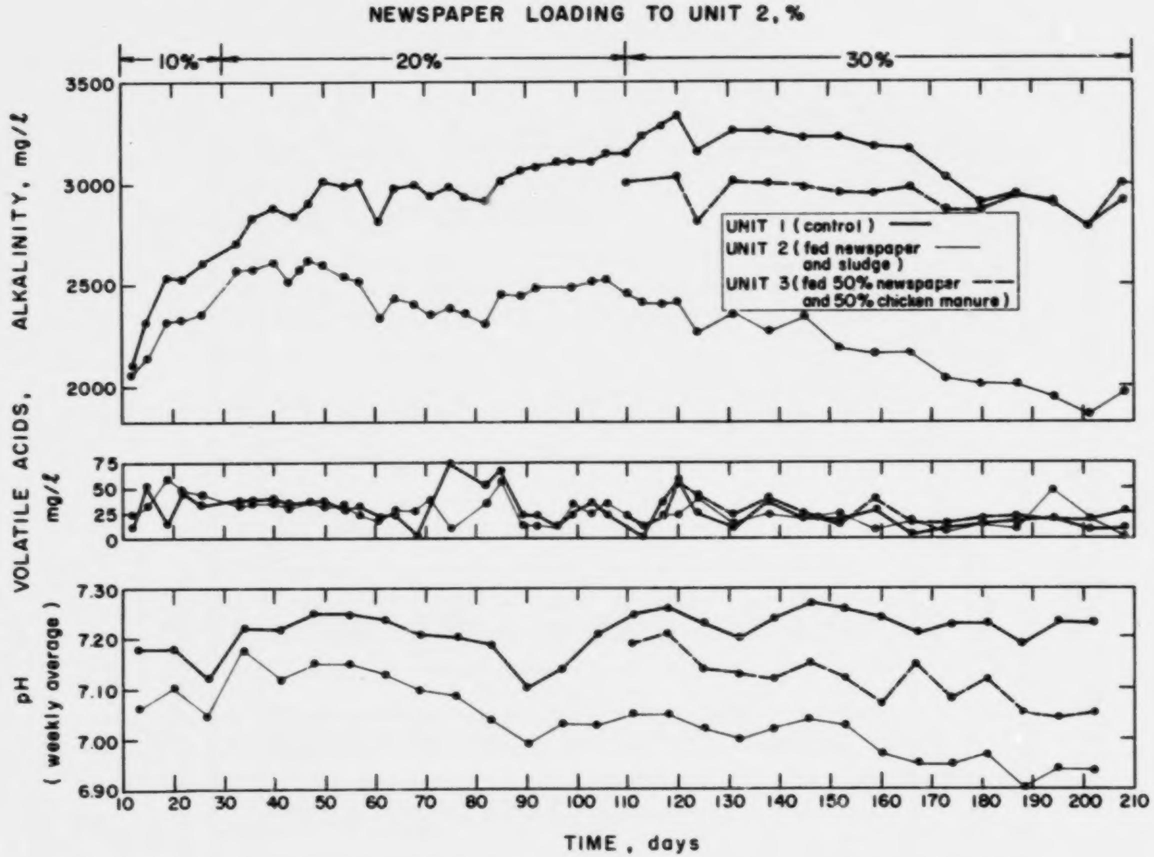


FIGURE 3. ACID - BASE EQUILIBRIA IN NEWSPAPER DIGESTION

SW 109

As shown by the data in Table 40, the composition of gas produced by the culture receiving newspaper and sludge was about the same as that from the culture fed only sludge. The methane content of gas from the former averaged 68.9%; and that from the latter, 70.0%.

TABLE 40

COMPOSITION OF GAS FROM CULTURES RECEIVING NEWSPAPER AND SLUDGE AND SLUDGE ONLY

Day	Methane, %			Carbon Dioxide, %		
	Unit 1[a]	Unit 2	Unit 12	Unit 1	Unit 2	Unit 12
14	69.9	67.8		30.1	32.2	
21	67.1	67.3		32.9	32.7	
28	67.1	66.0		32.9	34.0	
35	69.6	67.4		30.4	32.6	
42	70.7	69.0		29.3	31.0	
49	70.1	69.1		29.9	30.9	
56	70.0	69.5		30.0	30.5	
63	71.0	68.0		29.0	32.0	
70	70.2	70.1		29.8	29.9	
77	70.7	70.1		29.3	29.9	
84	68.9	68.9		31.1	31.1	
91	71.2	70.0		28.8	30.0	
98	69.7	68.1		30.3	31.9	
105	69.2	68.0		30.8	32.0	
112	68.9	69.0	68.2	31.1	31.0	31.8
119	70.0	68.6	67.5	30.0	31.4	32.5
126	70.6	68.5	67.4	29.4	31.5	32.6
133	69.3	69.1	63.0	30.7	30.9	37.0
140	69.0	68.0	65.1	31.0	32.0	34.9
147	69.7	68.0	66.2	30.3	32.0	33.8
154	68.5	68.8	66.5	31.5	31.2	33.5
161	69.6	68.2	--	30.4	31.8	--
168	70.3	69.1	68.8	29.7	30.9	31.2
175	77.5	75.5	68.6	22.5	24.5	31.4
182	70.3	69.2	63.0	29.7	30.8	37.0
189	71.5	69.6	64.9	28.5	30.4	35.1
196	69.4	70.0	64.7	30.6	30.0	35.3
203	70.0	69.5	65.1	30.0	30.5	34.9
AVG.	70.0	68.9	66.1	30.0	31.1	33.9

[a] Control - fed 100% sludge

A summary of results pertaining to the digestion of newspaper is presented in Table 41. The data are averages of weekly analyses for the test digesters. The averages may be compared to the average results obtained with the control (sludge only) during the same experimental period. Values for the control are in parentheses.

SECOND EXPERIMENTAL SERIES – DIGESTION OF GRASS CLIPPINGS

The proportion of garden debris in urban solid wastes varies from one community to another. For example, it comprises 9% of the total in Santa Clara, and 5% in Berkeley. For the investigation of the digestibility of garden debris, grass clippings were chosen as representative of the many types of vegetation which fall into this general classification.

Procedure

Three digesters were placed in operation at a sludge loading of 0.077 lb/cu ft. One digester served as a control (unit 1). It received only sewage sludge. The other two digesters were adapted to a feed containing 50% grass by increasing the grass content of the feed mixture by 5% increments over a 35-day period. The second digester (unit 4) was then fed 50% grass and 50% sludge throughout the experimental period. The third digester (unit 3) was converted to 50% grass and 50% chicken manure. Subsequent to the acclimation period for both digesters, the duration of the experiment was 65 days.

Initially, an attempt was made to digest grass clippings without any form of preliminary grinding or processing. This proved unsatisfactory because the waxy surface of grass prevented adequate wetting and access by bacteria. Grinding sufficiently to bruise the surface of the grass blades proved acceptable. However, because a hammermill was at hand, the grass clippings were ground to a powder in the mill.

Results

The grass proved readily digestible, combinations of grass and sludge digested more readily than mixtures of grass and chicken manure. The parameters of efficiency as given in Figure 4 indicate that digestion of the grass-sludge mixture (unit 4) was almost identical to that of sludge alone in reduction of cellulose, volatile solids, and total solids, although the gas yield was somewhat less. Average gas production per pound of volatiles added to the culture fed grass and sludge was 7.8 cu ft, as is shown by the data in Table 42. Gas production by the control digester (sludge only) was 9 cu ft/lb volatile solids introduced. Gas production by the digester fed grass and chicken manure averaged 5.9 cu ft, or 34.5% less than that by the control. A calculation based on the digestibility of sewage sludge showed that the grass clippings were about 73% digestible. The average reduction in the cellulose content of the grass-sludge mixture was 79.5% (1.1% less than the control). The calculated destruction of cellulose in the grass clippings averaged 78.5%.

The acid-base parameters of the test units followed a pattern similar to those of digesters fed garbage. They were described in the First and Second Annual Reports. The continuous rise in alkalinity and pH which took place in the culture is shown in Figure 5. The rise indicates deamination of the grass feed. As a result, an increase in ammonium carbonate concentration took place and the net alkalinity increased. The lowering of the C:N ratio brought about by the addition of garden debris, green garbage, and chicken manure, apparently led to a high degree of buffering capacity in the digester.

As shown by the data in Table 43 the gas composition for all three units was virtually the same. A summary of the results obtained in the experiment is given in Table 44.

TABLE 41

SUMMARY OF RESULTS PERTAINING TO THE DIGESTION OF NEWSPAPER

Parameter	Unit 2 - Newspaper Content in Sludge Feed			Unit 12 50% Chicken Manure 50% Newspaper
	10%	20%	30%	
Efficiency of Newspaper Digestion, %	8.0	53.5	44.3	--
$\frac{\text{cu ft Gas Produced}}{\text{lb VS Added}}$	9.9 (10.9)[a]	8.8 (9.7)	7.5 (9.0)	4.1 (9.0)
$\frac{\text{cu ft Gas Produced}}{\text{lb VS Destroyed}}$	15.4 (17.0)	15.2 (16.2)	13.0 (13.1)	12.4 (13.3)
VS Reduction %	64.4 (65.7)	55.4 (59.4)	58.0 (69.4)	32.4 (68.4)
TS Reduction %	53.1 (52.8)	44.3 (45.7)	47.5 (53.5)	23.1 (52.2)
Cellulose Reduction %	82.8 (87.9)	73.3 (81.7)	63.0 (79.9)	46.7 (79.9)
Efficiency of Newspaper Cellulose Reduction, %	55.0	49.6	41.7	--
Methane %	67.1 (68.4)	69.0 (70.0)	69.5 (70.5)	66.1 (70.5)
CO_2 %	32.9 (31.6)	31.0 (30.0)	30.5 (29.5)	33.9 (29.5)
pH	7.10 (7.17)	7.07 (7.21)	6.98 (7.23)	7.11 (7.23)
Alkalinity mg/ℓ	2620 (2488)	2440 (3042)	2120 (3075)	2950 (3117)
Volatile Acids mg/ℓ	38 (30)	29 (39)	18 (15)	24 (18)

[a] Control - 100% Sludge

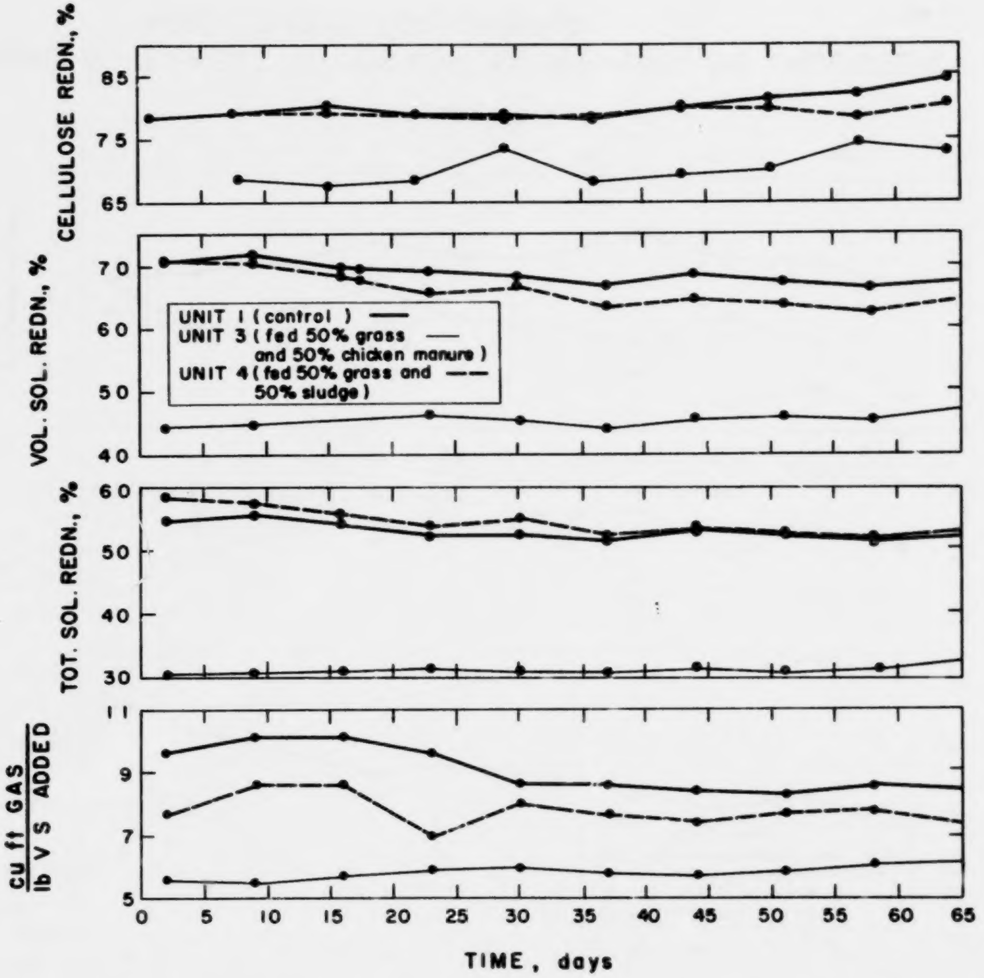


FIGURE 4. EFFICIENCY OF GRASS CLIPPINGS DIGESTION

SW 110

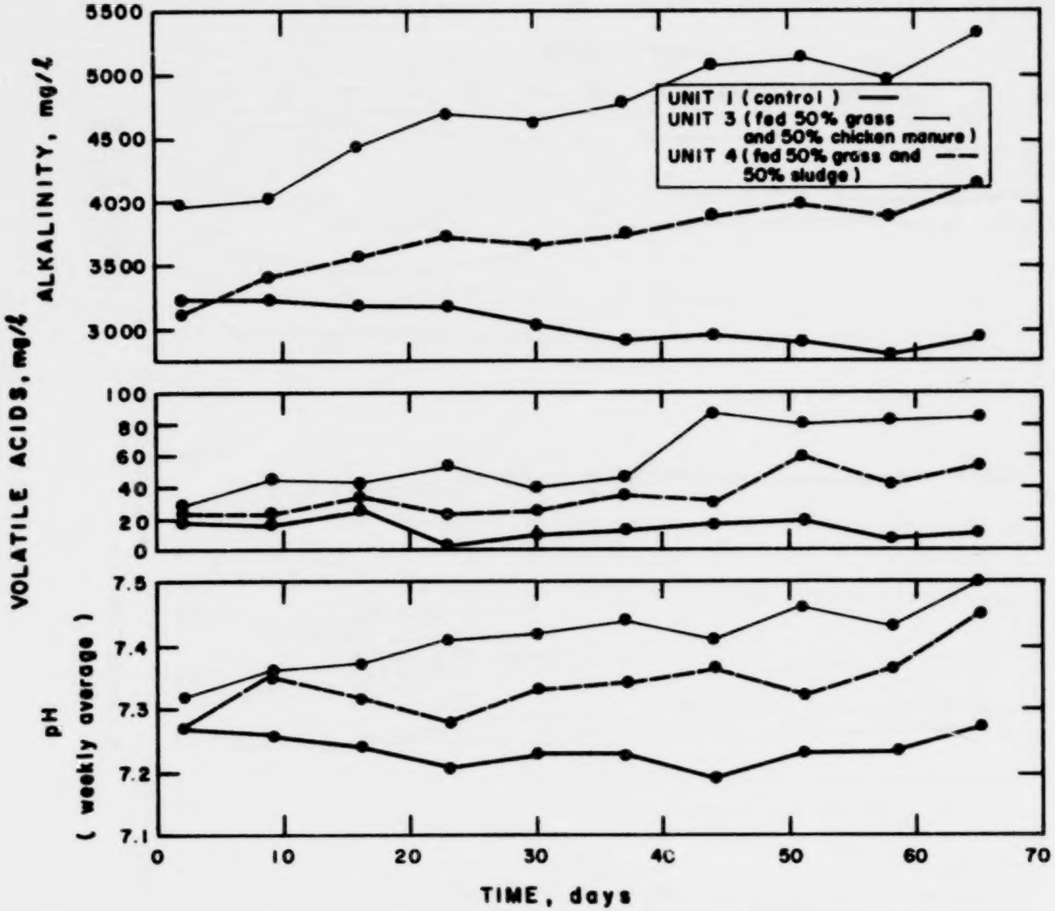


FIGURE 5. EFFECT OF GRASS CLIPPINGS ON DIGESTER ACID-BASE EQUILIBRIA

SW III

TABLE 42

GAS PRODUCTION PER UNIT OF VOLATILE SOLIDS ADDED TO THE DIGESTER RECEIVING GRASS CLIPPINGS

Day	Unit 1		Unit 3		Unit 4	
	Added	Destr.	Added	Destr.	Added	Destr.
2	9.6	13.6	5.6	12.6	7.7	10.9
9	10.1	14.1	5.5	12.2	8.6	12.2
16	10.1	14.7	-	-	8.6	12.5
23	9.6	14.0	5.9	12.7	6.9	10.5
30	8.6	12.6	6.0	13.1	8.0	11.9
37	8.6	13.0	5.8	13.1	7.7	12.1
44	8.4	12.3	5.7	12.3	7.4	11.4
51	8.3	12.4	5.9	13.2	7.7	12.0
58	8.6	12.9	6.1	13.3	7.8	12.5
65	8.5	12.6	6.2	13.0	7.4	11.5
AVG.	9.0	13.2	5.9	12.8	7.8	11.9

THIRD EXPERIMENTAL SERIES – DIGESTION OF ANIMAL MANURE

In previous experiments, the possibility of disposal of animal manures by anaerobic digestion was explored only incidentally, in that chicken manure was used instead of sludge as a nitrogen source when studying the digestibility of other solid waste materials. In the present study, cow and chicken manure were digested individually and in combination with each other. In addition, steer manure was combined with sludge and grass to determine the feasibility either of digesting them along with sewage sludge in municipal digesters, or of using them as a nitrogen source in digesters built especially for solid wastes.

Procedure

The test digesters in this study had all been operated previously on other solid wastes and were adapted over a two-week period to the following feed mixture:

Unit	Feed
1	100% Sludge
2	100% Steer Manure
3	50% Steer Manure, 50% Grass
4	50% Steer Manure, 50% Chicken Manure
B	100% Chicken Manure
C	50% Steer Manure, 50% Sludge .

Aside from the nature of the feed, other experimental conditions were the same as in the previous experimental series, i.e., constant temperature of 37°C, 30-day detention time, digester liquid capacity of 3 liters, organic loading of 0.077 lb volatile solids per cu ft of digester capacity per day (3.70 g/day), and mixing applied in units 1, 2, 3, and 4.

TABLE 43

COMPOSITION OF GAS FROM THE DIGESTER RECEIVING GRASS CLIPPINGS

Day	Methane, %			Carbon Dioxide, %		
	Unit 1	Unit 3	Unit 4	Unit 1	Unit 3	Unit 4
4	69.7	68.8	69.1	30.3	31.2	30.9
11	68.5	69.7	67.9	31.5	30.3	32.1
18	69.6	68.1	69.0	30.4	31.9	31.0
25	70.3	67.4	70.1	29.7	32.6	29.9
39	70.3	67.3	70.0	29.7	32.7	30.0
46	71.5	68.1	70.0	28.5	31.9	30.0
53	69.4	67.5	69.6	30.6	32.5	30.4
60	70.0	--	70.0	30.0	--	30.0
AVG.	69.9	68.1	69.5	30.1	31.9	30.5

Results

Very little gas was produced by the digester fed steer manure, as is shown by the data in Table 45. The average production was only 1.4 cu ft per lb of volatiles added. When chicken manure was digested, the yield was 5.0 cu ft per lb. The relative efficiency of the animals in utilizing the energy content of their diet is indicated by the difference in gas production from the digestion of their wastes. Thus, the energy content of steer wastes was much lower than that of chicken wastes, hence steers apparently utilize their food more efficiently than do chickens.

Using as a basis, gas production per pound of added volatile sewage solids in a digester fed sewage sludge, steer manure was 14.9% efficient and chicken manure 53.2% efficient. In terms of volatiles destroyed, the gas yield was higher from the digester-fed chicken manure than that from the sewage sludge digester.

Although the animal manures were stabilized by digestion and rendered inoffensive, there was virtually no reduction in volume of the material. Destruction of total solids was less than 15%, as is shown by the data listed in Table 46.

Experimental results presented in Table 47 indicate that performance of digesters was not hampered by the presence of manures. Regardless of which combination of steer manure or chicken manure with other solid waste was added, the pH of the culture remained higher than 7.2. A significant increase in volatile acids was noted in all test units, but average values were not exceptionally high at steady state. Apparently, the buffering capacity increased at a rate commensurate with the increase in acids. The increase in alkalinity indicates that a limited addition of manure would be helpful in stabilizing carbonaceous wastes. Probably, the acid would result from the lowering of the C:N ratio brought about by the nitrogen content of the manure.

According to the data given in Table 48, the composition of the gas from the digester fed manure was comparable to that of the gas from the sewage sludge digester. The methane content of the manure (digester) was only slightly less than that from the sludge digester. The maximum difference between the digester receiving only chicken manure and that fed sewage sludge are only 4.4%. All of the results are summarized in Table 49.

TABLE 44

SUMMARY OF RESULTS OBTAINED IN THE EXPERIMENTS ON THE DIGESTIBILITY OF GRASS CLIPPINGS

Parameter	Unit 1 100% Sludge	Unit 3 50% Grass 50% Ch. Man.	Unit 4 50% Grass 50% Sludge
[a]Efficiency of Grass Digestion, %	--	--	73.1
Cu ft Gas Produced Lb Vol. Sol. Added	9.0	5.9	7.8
Cu ft Gas Produced Lb Vol. Sol. Destroyed	13.2	12.8	11.9
Vol. Sol. Reduction %	68.7	45.5	66.2
Total Sol. Reduction %	52.9	31.1	54.3
Cellulose Reduction %	80.6	70.5	79.5
Efficiency of Grass Cellulose Reduction, %	--	--	78.5
Methane %	69.9	68.1	69.5
CO_2 %	30.1	31.9	30.5
pH	7.24	7.41	7.34
Alkalinity mg/ℓ	3030	4699	3705
Volatile Acids mg/ℓ	13	59	35

[a] Compared to Sludge

FOURTH EXPERIMENTAL SERIES – DIGESTION OF WHITE FIR WOOD

As was stated in the Second Annual Report, the significance of wood as a waste material to be processed in digesters derives from the possibility of disposing of demolition rubble and of tree trimmings and garden debris by way of sewerage systems. The reasons for investigating the digestion of wood or any other waste are manifold: 1) The toxic potential of wood or any waste must be evaluated to determine its suitability for contact with sensitive biological processes;

TABLE 45

GAS PRODUCTION PER UNIT OF VOLATILE SOLIDS ADDED BY A DIGESTER RECEIVING STEER MANURE

Day	Unit 1 100% Sludge		Unit 2 100% St. Man.		Unit 3 50% St. Man. 50% Grass		Unit 4 50% St. Man. 50% Ch. Man.		Unit B 100% Ch. Man.		Unit C 50% St. Man. 50% Sludge	
	Added	Destr.	Added	Destr.	Added	Destr.	Added	Destr.	Added	Destr.	Added	Destr.
5	9.4	14.0	1.0	11.0	4.1	7.2	2.9	17.1	--	--	--	--
12	8.7	13.1	1.0	7.2	4.1	7.5	3.1	18.1	5.2	--	4.8	8.1
19	9.0	13.5	1.2	9.0	4.2	8.1	3.3	16.9	1.9	9.2	5.1	8.9
26	9.3	13.8	1.3	9.4	4.5	8.9	3.3	15.9	1.9	9.5	4.7	8.6
33	9.3	13.8	1.3	9.5	4.4	8.9	3.3	16.5	3.5	22.9	5.6	11.9
40	10.1	14.8	1.7	10.1	4.3	9.2	3.3	13.0	4.8	29.5	5.6	11.3
47	9.8	14.8	1.8	9.5	3.3	7.4	3.3	20.1	6.7	37.9	3.5	7.1
54	10.1	14.8	1.7	9.0	4.5	10.0	3.3	13.7	4.3	15.1	3.3	7.0
61	9.7	14.3	1.6	7.9	4.5	10.0	3.2	13.4	5.3	17.6	4.2	9.7
68	10.1	15.1	1.5	9.5	4.5	10.2	3.4	15.1	5.4	19.8	7.7	17.3
75	9.6	14.3	1.4	7.0	4.3	9.2	3.4	13.9	5.2	17.3	5.7	11.7
82	9.1	13.3	1.7	6.8	5.2	11.0	4.1	14.3	5.6	16.9	5.5	10.8
89	8.7	14.7	1.3	7.0	4.2	9.2	3.5	14.5	4.6	16.4	4.2	9.4
96	8.7	14.9	1.7	8.5	3.9	8.8	3.5	15.2	8	16.6	4.6	11.6
AVG.	9.4	14.2	1.4	8.7	4.3	9.0	3.4	15.6	5.0[a]	17.1[a]	5.0	10.3

[a] Steady state average for Unit B (days 54 - 96)

TABLE 46

SOLIDS REDUCTION IN THE DIGESTION OF ANIMAL MANURE

Day	Unit 1 100% Sludge		Unit 2 100% St. Man.		Unit 3 50% St. Man. 50% Grass		Unit 4 50% St Man. 50% Ch. Man.		Unit B 100% Ch. Man.		Unit C 50% St. Man. 50% Sludge	
	Total	Vol.	Total	Vol.	Total	Vol.	Total	Vol.	Total	Vol.	Total	Vol.
1	55.8	70.4	6.0	8.7	46.5	60.4	9.5	15.3	--	--	--	--
8	54.4	69.1	6.5	9.5	45.3	58.9	10.8	17.4	--	--	--	--
15	55.1	69.5	10.0	14.5	44.4	57.9	11.0	17.7	--	--	45.6	61.8
22	55.5	70.0	9.6	14.0	41.5	54.0	12.9	20.7	12.4	22.1	44.2	59.9
29	56.3	71.0	10.0	14.5	40.7	53.0	13.5	22.0	11.9	21.1	42.8	58.0
36	55.9	70.5	10.0	14.5	39.7	51.7	13.4	21.3	9.0	15.9	36.3	49.7
43	56.4	72.0	11.9	17.2	38.0	49.3	16.1	26.2	9.6	16.9	37.8	51.6
50	54.3	69.5	13.5	19.7	35.9	46.6	10.8	17.4	10.5	18.6	37.4	51.1
57	55.1	71.5	13.3	19.4	36.5	47.4	15.7	25.4	17.1	30.1	36.5	49.8
64	55.9	71.4	15.0	21.3	36.7	47.8	15.5	25.2	18.0	31.7	33.4	45.6
67	54.8	70.0	11.3	16.4	35.9	46.6	14.7	23.9	16.2	28.7	34.1	46.6
78	55.3	70.6	14.5	21.0	38.0	49.3	16.0	26.0	17.7	31.7	37.4	51.1
84	56.2	71.7	17.6	25.3	38.0	49.3	18.8	30.3	19.5	34.6	39.4	53.8
91	50.9	61.9	13.4	19.3	36.7	47.8	15.5	25.1	16.6	29.7	36.3	47.2
98	50.6	61.4	14.9	21.6	36.3	47.1	15.0	24.2	17.2	30.4	32.5	41.8
AVG.	54.8	69.4	11.8	17.1	39.3	51.1	13.9	22.5	14.6	26.0	38.0	51.4

TABLE 47

ACID-BASE EQUILIBRIA IN THE DIGESTION OF ANIMAL MANURE

Day	Control 100% Sludge			Unit 2 100% St. Man.			Unit 3 50% St. Man. 50% Grass			Unit 4 50% St. Man. 50% Ch. Man.			Unit B 100% Ch. Man.			Unit C 50% St. Man. 50% Sludge		
	pH	Alk. mg/ℓ	Vol. Acids mg/ℓ	pH	Alk. mg/ℓ	Vol. Acids mg/ℓ	pH	Alk. mg/ℓ	Vol. Acids mg/ℓ	pH	Alk. mg/ℓ	Vol. Acids mg/ℓ	pH	Alk. mg/ℓ	Vol. Acids mg/ℓ	pH	Alk. mg/ℓ	Vol. Acids mg/ℓ
1	7.27	2850	24	7.30	2478	24	7.46	5083	132	7.43	4140	48	--	--	--	--	--	--
8	7.21	2789	24	7.31	2610	60	7.39	4663	190	7.35	4060	71	7.20	--	--	7.24	--	--
15	7.25	2917	24	7.33	2880	24	7.43	4792	144	7.36	4271	72	7.24	--	--	7.31	3051	24
22	7.24	2920	11	7.27	3040	20	7.38	4670	92	7.32	4292	67	6.99	3910	176	7.28	3040	22
29	7.20	2955	34	7.19	3070	43	7.29	4510	105	7.18	4160	45	6.83	4070	3500	7.21	2980	16
36	7.18	2940	27	7.17	3220	16	7.31	4470	16	7.27	4280	47	6.98	4170	3800	7.25	3045	38
43	7.25	2862	42	7.23	3321	131	7.40	4389	150	7.36	4290	161	7.29	4325	825	7.33	3100	74
50	7.25	2885	9	7.23	3360	30	7.41	4400	123	7.43	4300	43	7.52	4715	169	7.15	3130	671
57	7.26	2905	14	7.23	3425	25	7.39	4435	124	7.35	4330	55	7.43	4940	136	7.02	3210	1132
64	7.23	3870	21	7.27	3492	35	7.39	4421	104	7.37	4360	46	7.50	5040	81	7.12	3192	422
71	7.25	2895	23	7.26	3455	46	7.44	4360	115	7.35	4350	46	7.46	5020	126	7.41	3360	184
78	7.21	2902	27	7.21	3520	48	7.33	4340	80	7.27	4320	46	7.41	4970	107	7.34	3280	69
85	7.37	2950	48	7.24	3545	217	7.38	4430	71	7.34	4320	60	7.48	5080	99	7.42	3310	89
92	7.12	2840	37	7.26	3560	46	7.40	4140	152	7.27	4190	97	7.38	4860	240	7.29	3102	76
99	7.12	2820	0	7.22	3570	39	7.27	4330	74	7.28	4210	30	7.39	5010	116	7.22	3140	97
AVG.	7.23	2887	24	7.25	3236	54	7.38	4496	111	7.33	4258	62	7.29	4676	134[a]	7.26	3149	224

[a] Average at steady state

TABLE 48

COMPOSITION[a] OF DIGESTER GAS IN EXPERIMENTS ON THE DIGESTION OF MANURE

Day	Control		Unit 2		Unit 3		Unit 4		Unit B		Unit C	
	CO_2	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2	CH_4
19	36.7	63.3	31.5	68.5	37.7	62.3	23.4	76.6	39.4	60.6	36.7	63.3
26	34.7	65.3	33.4	66.6	38.0	62.0	20.5	79.5	46.7	53.3	34.0	66.0
33	34.6	65.4	32.2	67.8	37.4	62.6	36.7	63.3	46.4	53.6	34.1	65.9
40	36.9	63.1	31.9	68.1	37.7	62.3	39.0	61.0	41.9	58.1	35.7	64.3
47	37.0	63.0	33.6	66.4	38.8	61.2	--	--	37.5	62.5	36.6	63.4
54	36.0	64.0	34.7	65.3	38.7	61.3	38.9	61.1	35.2	64.8	38.5	61.5
61	36.6	63.4	37.2	62.8	39.3	60.7	36.2	63.8	36.3	63.7	39.9	60.1
68	35.9	64.1	37.1	62.9	39.0	61.0	37.5	62.5	38.4	61.6	36.8	63.2
75	34.0	66.0	36.8	63.2	40.3	59.7	39.9	60.1	39.3	60.7	33.8	66.2
82	35.8	64.2	38.6	61.4	37.8	62.2	39.1	60.9	38.6	61.4	36.0	64.0
89	35.2	64.8	35.7	64.3	37.9	62.1	37.5	62.5	42.1	57.9	34.6	65.4
AVG.[b]	35.8	64.2	34.8	65.3	38.4	61.6	38.1	61.9	40.2	59.8	36.1	63.9

[a] Normalized percent

[b] At steady state

TABLE 49

SUMMARY OF RESULTS OF THE EXPERIMENTS ON DIGESTION OF MANURE

Parameter	Unit 1 100% Sludge	Unit 2 100% St. Manure	Unit 3 50% St. Manure 50% Grass	Unit 4 50% St. Manure 50% Ch. Manure	Unit B 100% Ch. Manure	Unit C 50% St. Manure 50% Sludge
[a]Efficiency of Manure Digestion, %	--	14.9	--	36.2	53.2	6.2
$\frac{\text{cu ft Gas Produced}}{\text{lb Vol. Sol. Added}}$	9.4	1.4	4.3	3.4	5.0	5.0
$\frac{\text{cu ft Gas Produced}}{\text{lb Vol. Sol. Destroyed}}$	14.2	8.7	9.0	15.6	17.1	10.3
Vol. Sol. Reduction, %	69.4	17.1	51.1	22.5	26.0	51.4
Total Sol. Reduction, %	54.8	11.8	39.3	13.9	14.6	38.0
Methane, %	64.2	65.2	61.6	61.9	59.8	63.9
CO_2, %	35.8	34.8	38.4	38.1	40.2	36.1
pH	7.23	7.25	7.38	7.33	7.29	7.26
Alkalinity, mg/ℓ	2887	3236	4496	4258	4676	3149
Volatile Acids, mg/ℓ	24	54	111	62	134	224

[a]Compared to Sludge

2) the economic advantages of grinding to sewers and transport by the sewerage system must be estimated; and 3) a determination must be made of the benefits to be accrued from reducing the bulk of a given waste by digestion. Judging from experience of the digestion of Monterey pine wood, very little reduction in the bulk of any material containing wood would take place, probably because of the resistance of lignin to anaerobic digestion.

A fourth purpose evolved from the findings of the previous study, namely, to determine the effect of a waste on the physical characteristics of sludge effluent from the digester. Monterey pine wood had a blanketing effect on the sludge which interfered with circulation and mixing. This was quite noticeable when normal sampling procedures were practiced. The subsidence of sludge took place so rapidly following mixing that it was impossible to obtain representative examples of the digester's solids content.

Although Monterey pine could not be digested, it had no observable toxic effect on the digestion process. Monterey pine belongs to a group of conifers characterized by a high content of pitch and resins. These substances may be very toxic to a digester culture. Other conifers, of which white fir is an example, have a low pitch and resin content, and hence should not affect the digestion process adversely because of toxicity. However, the wood may inhibit digestion in other ways. It could have the blanketing effect of rapid settling noted with Monterey pine. If so, the purposeful addition of a woody material to a digester would be undesirable because it would hasten the buildup of bottom sludges; which in turn would necessitate more frequent shutdowns for the cumbersome task of a clean-out.

Procedure

Three digesters of 3-ℓ capacity each were operated at a loading of 0.077 lb volatile solids per cu ft of digester capacity per day. Throughout the experimental period of 107 days, the feed composition to the units was as follows:

Unit 1 - 0% white fir, 100% sludge

Unit 3 - 10% white fir, 90% sludge

Unit 4 - 60% white fir, 40% sludge

Mixing was accomplished by automatic mixing devices which were activated for 1.5 minutes each hour. The units were maintained at 37°C throughout the study.

Results

Gas production on the basis of volatile solids added is indicated by the curves in Figure 6. Unit 1, the control (fed sewage sludge), averaged 10.1 cu ft/lb; unit 3 (10% white fir), averaged 9.3 cu ft/lb; and unit 4 (60% white fir), averaged 4.3 cu ft/lb. The digestion efficiencies of the digesters fed white fir calculated by way of the formula given in Materials and Methods were found to be 20% for the unit receiving 10% white fir, and 4.4% for the one receiving 60% white fir. The results obtained with unit 4 probably are the more reliable than those from unit 3, because the former received six times as much wood as did the latter, and consequently any effect due to experimental error was correspondingly reduced.

Other parameters of digestion efficiency, such as total and volatile solids reduction and cellulose reduction, should not be taken at face value because the rapid subsidence of the sludge precluded representative sampling of digester contents. This can be readily demonstrated by the data on destruction of cellulose as presented in Table 50. If the values shown in the table were correct, then approximately 50% of the cellulose input derived from white fir was destroyed in unit 4. This was calculated from the cellulose inputs listed in Table 51 as follows:

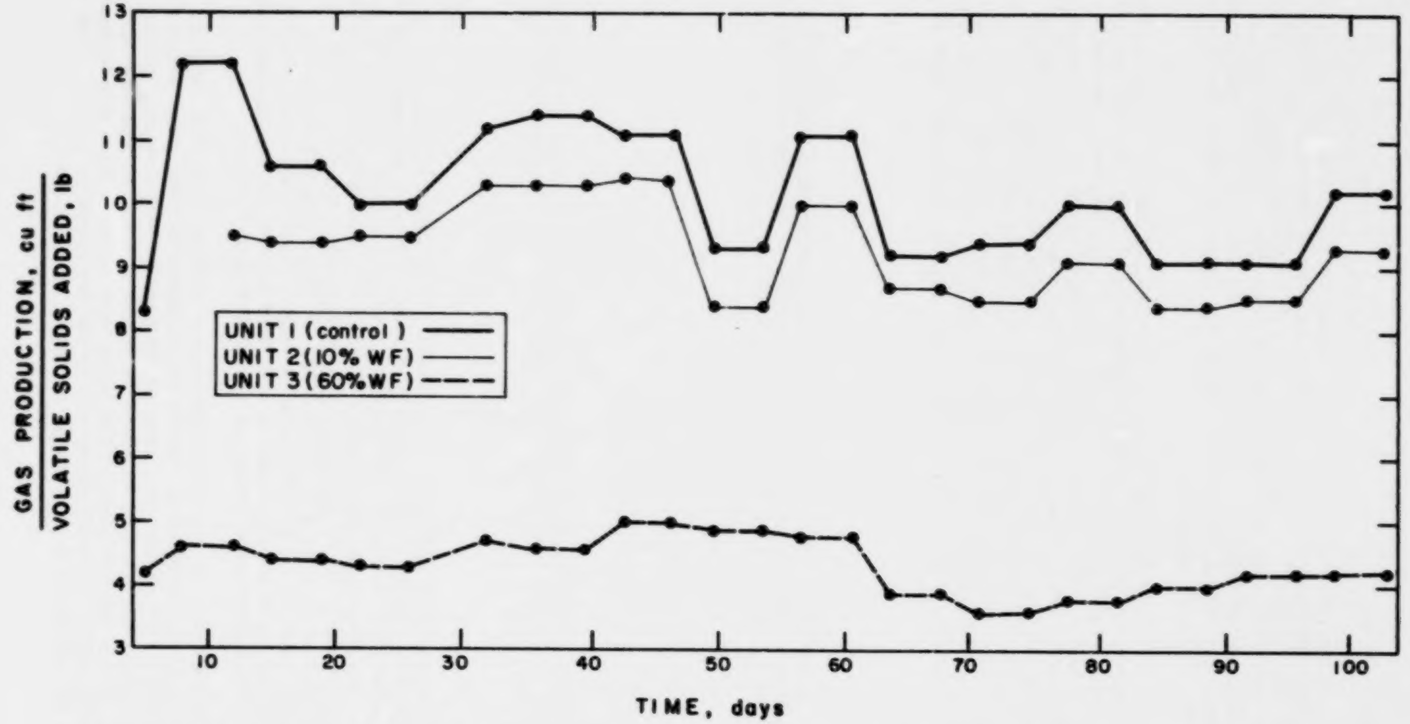


FIGURE 6. GAS PRODUCTION EFFICIENCY RELATIVE TO ADDED VOLATILE SOLIDS
(DIGESTERS FED WHITE FIR)

SW 112

TABLE 50

APPARENT DESTRUCTION OF CELLULOSE IN THE DIGESTERS RECEIVING WOOD

Day	1, 100% Sludge		3, 90% Sludge, 10% WF		4, 40% Sludge, 60% WF	
	Residual Cellulose g/100 mℓ	Destruction %	Residual Cellulose g/100 · mℓ	Destruction %	Residual Cellulose g/100 mℓ	Destruction %
4	0.168	90.3	0.156	91.5	0.196	91.7
11	0.220	87.5	0.260	85.9	0.320	86.5
18	0.188	89.2	0.224	87.9	0.568	75.9
25	0.148	91.5	0.288	84.4	0.972	58.9
32	0.232	86.6	0.384	79.2	0.788	66.6
39	0.264	84.8	0.336	81.8	0.880	62.7
46	0.272	84.3	0.368	80.0	0.632	73.2
53	0.308	82.2	0.436	76.3	1.136	51.8
60	0.280	83.9	0.432	76.5	0.884	62.5
67	0.272	84.3	0.436	76.3	0.992	58.0
74	0.336	80.7	0.424	77.0	1.304	44.5
81	0.272	84.3	0.440	76.1	1.144	51.5
88	0.308	82.2	0.444	75.9	0.500	78.7
95	0.360	79.2	0.488	73.5	0.656	72.2
102	0.340	80.4	0.436	76.3	0.796	66.3
109	0.420	75.8	---	--	---	--
AVG.	0.274	84.2	0.370	79.9	0.890[a]	62.1[a]

[a] Day 25 - 102 considered steady state.

TABLE 51

DAILY INPUT OF CELLULOSE TO DIGESTERS RECEIVING WOOD

To Unit	Cellulose Added, grams		
	From Sludge Feed	From White Fir	Total
1	1.736	0	1.736
3	1.560	0.370	1.930
4	0.700	1.650	2.350

1. Control (sewage sludge only) cellulose destruction equals 84.2%.
2. Unit 4 (10% white fir, 90% sewage sludge) cellulose input from sludge equals 0.70 g/day.
3. Cellulose residual attributed to sewage sludge equals 0.70 x 0.158 equals 0.111.
4. Average cellulose residual equals 0.890 g.
5. Cellulose residual attributed to white fir equals 0.890 - 0.111 = 0.779 g.
6. Percent destruction of white fir cellulose equals 1.65 - 0.779/1.65 x 100 = 52.9.

To have a 50% cellulose destruction without gas production could only mean that either degradation proceeded only to the volatile acid stage of fermentation, or that nonrepresentative samples were taken. Since the volatile acid content remained constantly low as is shown by the curves in Figure 7, the former possibility must be rejected, and it must be concluded that the samples were not representative. This leaves the conclusion that the white fir was not degraded, and furthermore that it had the same blanketing effect as did Monterey pine. The results, real and apparent, are listed in Table 52. (Results pertaining to volatile and total solids destruction are only apparent. The reasons are the same as those applied to cellulose destruction.)

The experiments indicate that the addition of small amounts of wood to a digester would exert neither a chemically nor a physically adverse effect on the culture. Even with the addition of a high percentage of wood no adverse functional effects were noted. Apparently, the main objection to adding wood to a digester would be that it would settle out and cause a more rapid than normal accumulation of bottom sediment. There seems little likelihood than the problem of too much wood in the feed to a digester would occur under practical conditions. For example, a Santa Clara study showed that the amount of wood in the city's refuse was only 2% of the total refuse.

FIFTH EXPERIMENTAL SERIES - DIGESTION OF COMPOSITE ("SYNTHETIC") REFUSE

In this series of experiments a "synthetic" refuse was digested with sewage sludge. The ratios of the two (refuse and sewage sludge) were based on the amounts

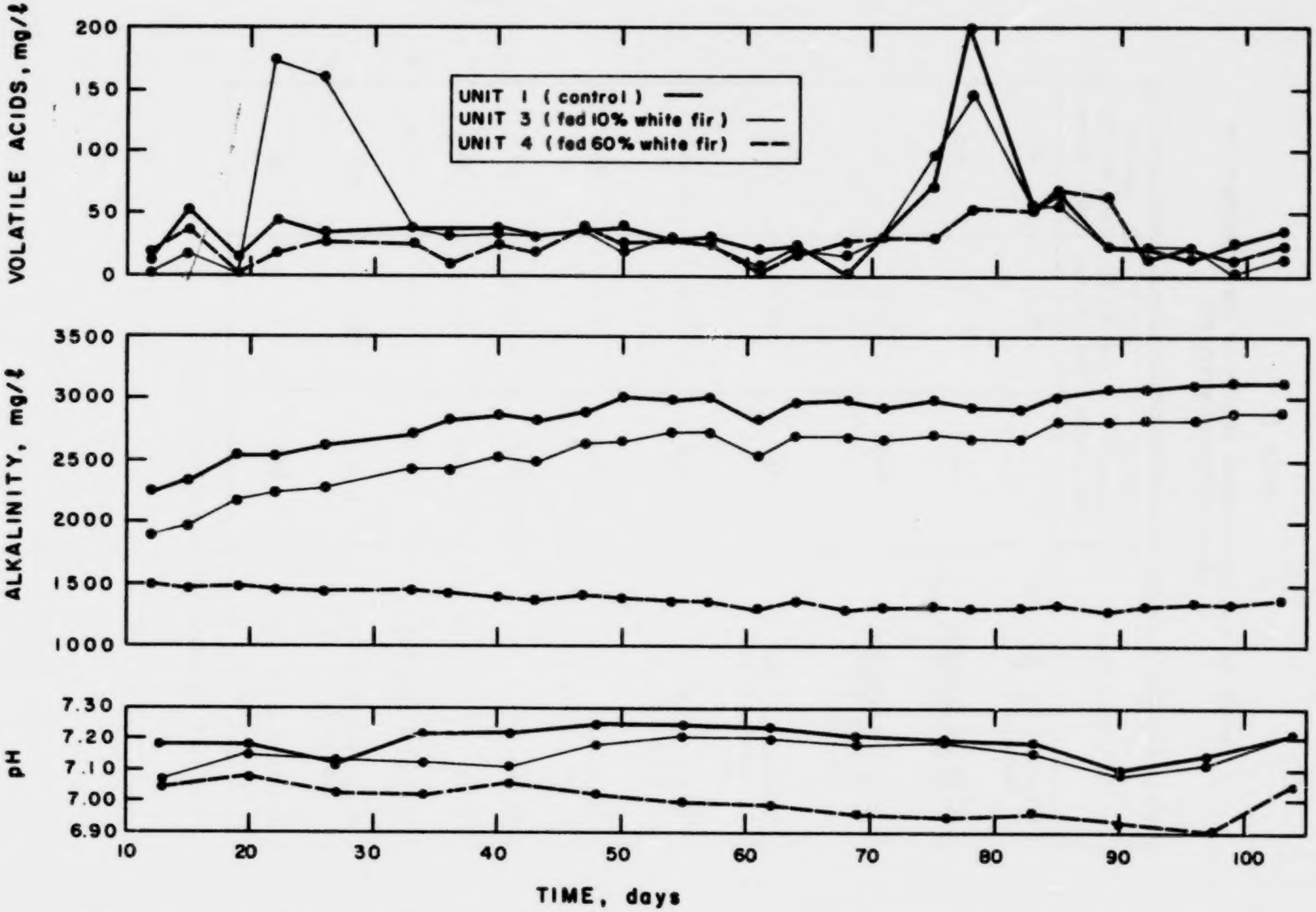


FIGURE 7. ACID - BASE EQUILIBRIA IN WHITE FIR DIGESTION

SW 113

TABLE 52

SUMMARY OF REAL AND APPARENT RESULTS OF THE EXPERIMENTS ON THE DIGESTION OF WHITE FIR

Parameter	Unit 1 Control 100% Sludge	Unit 3 10% Wh. Fir 90% Sludge	Unit 4 60% Wh. Fir 40% Sludge
Efficiency of White Fir Digestion, %	--	20.0	4.4
cu ft Gas Produced / lb Vol. Solids Added	10.1	9.3	4.3
cu ft Gas Produced / lb Vol. Solids Destroyed	16.6	15.1	7.7
[a]Volatile Solids Reduction, %	60.7	60.5	50.4
[a]Total Solids Reduction, %	46.4	47.8	46.4
[a]Cellulose Reduction, %	84.2	79.9	62.1
Methane %	69.8	68.9	69.7
CO_2 %	30.2	31.1	30.3
pH (daily samples)	7.19	7.15	7.01
Alkalinity mg/ℓ as $CaCO_3$	2823	2500	1390
Volatile Acids mg/ℓ as acetic	37	44	33

[a] See text regarding sampling difficulties

relative to each other generated per capita. Therefore, the results obtained in this series of experiments are those which one would expect were all organic solid wastes digested in an existing sewage treatment system suitably expanded to handle the additional loading.

Formulating the Synthetic Refuse

The composition of the mixture was based primarily on the results of the analysis made of Berkeley refuse in the first year of the overall project and reported in the First Annual Report [4]. The analysis showed that about 25% of the domestic refuse processed at the site was garbage and garden debris; soiled paper, 35%; and clean paper, about 10%. Of the garbage and garden debris mixture about 80% was garbage. Composition of the Berkeley refuse was quite similar to that of refuse generated in Santa Clara County. Garbage constituted about 12% of the Santa Clara refuse; paper, 50%; wood, 2%; and garden wastes, 9%.

Since the per capita production in the two areas was about 3.5 pounds "wet" weight/day, this value was used in making up the feed. To allow for wood wastes, wood was included and constituted 2% of the "synthetic" refuse. In setting up the proportions of solid wastes to sewage sludge, the dry weights of the two classes of wastes were used as the basis. The dry weights of the various components of the "synthetic" refuse were estimated as shown in Table 53.

TABLE 53

ESTIMATING THE DRY WEIGHTS OF THE COMPONENTS OF THE "SYNTHETIC" REFUSE

Material	% of Total (Total = 3.5 lb)	Wet Weight lb	Moisture %	Dry Weight lb
Garbage	20.0	0.700	75.0	0.175
Garden Debris (grass)	5.1	0.178	24.8	0.089
Paper (soiled)	34.7	1.210	30.0	0.850
Paper (clean)	9.9	0.346	5.6	0.326
Wood	2.0	0.070	9.3	0.063

The paper fraction was further quantified on the basis of the relative amounts of Kraft and newspaper to be encountered in refuse. As mentioned previously in the experiments on newspaper, the difference in digestibility between Kraft and newsprint is considerable (Kraft is greater than 90%, newsprint equals 48%), and a realistic estimate of their ratio in wastes must be made in setting up a representative "synthetic" waste. Based on annual domestic consumption figures (1964) of 8,247,000 tons of newsprint and 9,900,000 tons of Kraft, the percentage of each in paper wastes was calculated. No adjustment was made for salvage, since a ratio of 1:1 (estimated by the American Paper Institute) is recycled. Thus, of the 1.176 pounds (dry weight) of paper consumed per person per day, 54.6% (0.642 pound) is Kraft, and 45.4% (0.534 pound) is newsprint. Based on a loading of 0.077 pound/day (3.70 g VS/day), the feed mixture had the composition shown in Table 54.

TABLE 54

COMPOSITION OF FEED MIXTURE OF "SYNTHETIC" REFUSE AND RAW SEWAGE SLUDGE

Material	Volatile Solids (g)	% of Feed Mixture
Garbage	0.398	10.8
Grass	0.204	5.5
Newspaper	1.218	32.9
Kraft paper	1.460	39.5
White fir	0.144	3.9
Sludge	0.274	7.4
Total	3.698	100.0

Experimental Procedure

Four of the five digesters were operated at different loading rates. Fifty percent of the loading to the fifty digester (unit C) was in the form of sewage sludge, while the amount of "synthetic" refuse was reduced accordingly. The loading to each of the units is listed in Table 55. In summary, the basic loading variables were double loading at 30 days detention (unit 4), and single loading at 30, 20, and 15 days.

TABLE 55

LOADING TO THE DIGESTER RECEIVING "SYNTHETIC" REFUSE

Detention Time (days)	Unit	Loading	
		g/day	mℓ/day
30	2	3.70	100
20	1	5.50	150
15	3	7.40	200
30	4	7.40	100
30	C	3.70	100

The duration of the experiment was 152 days for units 1 through 4, including the acclimation period which varied for each unit. The standard mixing procedure was applied to the units, as well as standard measurements of performance parameters. In addition, the theoretical maximum hydraulic loading was determined by deriving kinetic constants for the rate of the hydrolysis of cellulose. Unit C was operated for 96 days. Its results are reported separately from those of the other units.

Results

The results obtained in the experimental run are summarized in Table 56. In the digester receiving equal proportions of raw sewage sludge and "synthetic" refuse, the alkalinity concentration stabilized above 1,700 mg/ℓ and the pH remained constant at or near 7.0. Solids reduction was only fair in the digester and reflected the resistance of the newspaper portion of the feed mixture to biological degradation. Total solids reduction averaged 43.8%; and volatile solids reduction, 51.9%. Cellulose reduction averaged 65.1%. The calculated amount of destruction of the cellulose in the solid waste was 54.8%. Gas production by the digester was about 56% of that by digesters receiving raw sewage sludge (i.e., 56% of 10 cu ft gas/lb volatile solids added).

Increasing the refuse portion of the mixture from 50% to 92.6%, as was done in units 1 to 4, altered the performance considerably. Since the four units received only 7.4% sewage sludge, the nitrogen content of the feed was reduced to a point at which the C:N ratio was 48.1. Previous results (paper pulp digestion) have indicated that the C:N ratio is the borderline at which a proper acid-base relationship can be maintained.

Alkalinity declined rapidly in each unit, and corrective measures were taken when volatile acids began to accummulate. Alkalinity was increased by adding lime or sodium bicarbonate. In Table 57 are shown the amounts of lime or $NaHCO_3$ added weekly to each unit to maintain an alkalinity above 2,000 mg/ℓ (as CO_3). The quantities required for each unit were proportional to unit detention time. The 30-day digesters (2 and 4) required additions of approximately 500 mg/ℓ per week; the 20-day digester (unit 1) required 750 mg/ℓ per week, while the 15-day digester (unit 3) required almost 1,000 mg/ℓ per week.

The corrective measures were taken belatedly for unit 1, and as a consequence the volatile acids concentration could not be effectively controlled for some time. Several weeks were required to bring the concentration down from a peak of 4,975 mg/ℓ to a stable operating level of approximately 300 mg/ℓ.

The composition of the gas from the various digesters is indicated in Table 58. Apparently the detention period had some slight influence on the composition of the gas. The methane content declined from 58.1% with the detention period at 30 days to 56.4% at 20 days, and 55.8% at 15 days. Compared to that produced in normal sludge digestion, the gas quality of these digesters was poor, in that it had from 10% to 15% less methane content. This again demonstrates the effect of a high carbon to nitrogen ratio in the feed on the percentage of methane produced.

Kinetics of the Digestion Rate of the Cellulose in the "Synthetic" Refuse

The kinetics of refuse digestion were characterized by using the Machaelis-Menten model and the cell continuity equation discussed in the section on theory in the introductory portion of this section of the report. Kinetic constants were derived for the microbiological cultures used in this experiment. Since in practice mixed refuse contained over 80% cellulose, cellulose concentration was used to represent substrate concentration. The basic data required for this kind of characterization are presented in Table 59. Cellulose input and output data were

TABLE 56

EFFICIENCY AND PERFORMANCE OF THE DIGESTERS RECEIVING "SYNTHETIC" REFUSE AND SEWAGE SLUDGE

Day	Solids Redn.		Gas Prodn. cu ft/day	CF/lb Added	CF/lb Destr.	Cellulose			Gas Comp.		pH wkly. avg.	Alk. mg/ml	V A mg/ml
	Total %	Vol. %				Infl. mg/ml	Effl. mg/ml	Destr. %	CO_2 %	CH_4 %			
5	43.4	50.5	0.0644	7.9	15.6	23.86	9.60	59.8	38.6	61.4	7.06	1890	11
12	45.8	53.1	0.0463	5.7	10.7	23.86	10.02	56.9	39.8	60.2	7.08	1840	22
19	41.9	49.6	0.0646	7.9	16.0	23.86	8.82	62.8	39.6	60.4	7.07	1790	21
26	43.0	51.1	0.0654	8.0	15.7	23.86	12.19	49.0	39.2	60.8	7.03	1770	11
33	41.9	49.8	0.0618	7.6	15.2	23.86	7.72	67.7	41.2	58.8	7.03	1710	21
40	39.8	47.4	0.0617	7.5	16.0	23.86	7.86	67.1	40.6	59.4	6.98	1720	64
48	43.0	51.1	0.0620	7.6	14.9	23.86	8.81	63.1	39.8	60.2	6.95	1680	20
54	45.2	53.9	0.0606	7.4	13.8	23.86	6.54	72.6	41.4	58.6	7.01	1675	21
61	41.4	49.5	0.0690	8.4	17.1	23.86	7.24	69.7	37.7	62.3	7.02	1680	6
68	48.1	57.5	0.0463	5.7	9.9	23.86	7.45	68.9	40.7	59.3	7.02	1660	36
75	45.4	54.4	0.0670	8.2	15.1	23.86	7.15	70.1	39.2	60.8	7.02	1750	27
82	43.6	52.1	0.0682	8.4	16.0	23.86	7.44	68.0	40.2	59.8	7.03	1740	--
89	46.4	54.4	0.0665	8.2	15.1	23.86	7.45	68.8	40.5	59.5	7.05	1770	71
96	44.0	52.3	0.0651	8.0	15.2	23.86	--	--	39.3	60.7	7.04	1760	38
AVG.	43.8	51.9	0.0621	7.6	14.7	23.86	8.33	65.1	39.8	60.2	7.03	1745	28

TABLE 57

ACID-BASE EQUILIBRIA IN DIGESTERS RECEIVING "SYNTHETIC" REFUSE

Day	Unit 2 (30-day detention time)				Unit 1 (20-day detention time)				Unit 3 (15-day detention time)				Unit 4 (30-day detention time) (2 x loading)			
	pH wkly avg.	Vol. Acids mg/ℓ	Alkalinity		pH wkly avg.	Vol. Acids mg/ℓ	Alkalinity		pH wkly avg.	Vol. Acids mg/ℓ	Alkalinity		pH wkly avg.	Vol. Acids mg/ℓ	Alkalinity	
			Total mg/ℓ	Added[a] mg/ℓ			Total mg/ℓ	Added[a] mg/ℓ			Total mg/ℓ	Added[a] mg/ℓ			Total mg/ℓ	Added[a] mg/ℓ
7	7.03	--	3170	--	7.02	--	2690	--	7.17	--	3725	--	7.16	--	3800	--
14	7.03	34	2830	344	7.01	34	2450	452	7.12	54	3180	--	7.16	46	3380	--
21	7.07	28	2650	--	7.05	21	2710	264	7.05	14	2560	--	7.09	37	3080	--
28	7.02	29	2460	580	7.02	36	2155	681	7.02	47	2730	900	7.08	34	2810	638
35	7.08	99	2570	--	7.03	30	2330	301	7.03	46	2545	750	7.04	75	2880	--
42	7.04	213	2150	--	6.95	9	1699	200	6.89	71	1850	400	6.99	18	2585	--
49	7.04	75	1950	--	6.98	34	1560	500	6.87	27	1800	500	7.00	37	2340	--
56	6.92	304	1713	600	6.93	199	1755	1525	6.88	59	1680	1500	6.94	23	2110	1200
63	7.09	1020	2960	1375	6.82	1285	2730	1600	7.05	78	2480	600	7.09	29	3010	600
70	7.16	1045	3130	1200	6.78	3920	4140	1040	7.02	118	2190	800	7.11	24	3130	--
77	7.06	103	2780	600	6.82	4975	4900	2056	7.02	165	2150	900	7.06	33	2650	600
84	7.26	42	3110	600	7.04	4080	5370	2056	7.03	74	2335	600	7.07	42	2610	600
91	7.15	49	2740	600	7.02	3140	4530	--	6.98	64	2130	1000	7.01	74	2790	600
98	7.16	64	2790	600	7.11	1930	3580	600	7.01	150	2220	1000	7.08	75	2750	600
105	7.27	--	2750	600	7.19	--	3040	600	7.04	--	2160	1200	7.15	--	2915	400
112	7.22	18	2830	400	7.03	366	2840	400	7.00	53	2460	800	7.01	47	2890	400
119	7.26	31	2750	400	6.99	261	2170	1000	7.03	52	2390	600	7.08	31	2870	400
126	7.09	9	2600	--	7.04	302	2610	--	6.94	25	2130	1000	6.95	72	2530	700
133	7.21	73	2870	700	7.02	381	2950	1000	6.97	109	2450	1000	7.01	145	2962	--
140	7.15	22	2410	800	7.08	212	2240	1000	6.98	45	2720	--	6.96	54	2500	600
147	7.16	15	2680	400	7.15	244	2390	800	7.05	32	1960	1200	6.97	47	2810	400
154	7.13	17	2540	600	7.08	408	2450	600	7.00	31	2190	1000	7.00	25	2620	400
AVG.[b]	7.18	33	2696	567[c]	7.07	339[d]	2521[d]	790[c]	7.00	62	2281	978[c]	7.02	63	2764	513[c]

[a] To maintain pH control it was necessary to add alkalinity (as either $CA(OH)_2$ or $NaHCO_3$). Figures shown for alkalinity are mg/ℓ as $CaCO_3$.

[b] (91 - 154)

[c] (per week)

[d] From day 112 to 154.

TABLE 58

COMPOSITION OF GAS FROM DIGESTERS RECEIVING "SYNTHETIC" REFUSE AND SEWAGE SLUDGE

Day	Methane, %				Carbon Dioxide, %			
	2 30-day	1 20-day	3 15-day	4 30-day 2x	2 30-day	1 20-day	3 15-day	4 30-day 2x
7	59.3	65.9	62.0	58.1	40.7	34.1	38.0	41.9
14	69.0	63.7	59.8	60.9	31.0	36.3	40.2	39.1
21	63.6	58.8	55.5	57.5	36.4	41.2	44.5	42.5
28	--	56.4	55.6	52.7	--	43.6	44.4	47.3
35	--	56.2	54.8	55.3	--	43.8	45.2	44.7
42	54.5	--	55.1	55.3	45.5	--	44.9	44.7
49	55.7	54.1	56.5	56.4	44.3	45.9	43.5	43.6
56	67.9	54.4	54.7	55.4	32.1	45.6	45.3	44.6
63	51.6	55.1	54.8	56.5	48.4	44.9	45.2	43.5
70	48.7	47.1	47.9	56.7	51.3	52.9	52.1	43.3
77	58.7	47.3	54.5	55.5	41.3	52.7	45.5	44.5
84	56.5	54.4	58.8	57.1	43.5	45.6	41.2	42.9
91	66.7	59.5	54.4	55.9	33.3	40.5	45.6	44.1
98	56.0	--	--	55.7	44.0	--	--	44.3
105	55.9	63.2	56.1	--	44.1	36.8	43.9	--
112	--	61.7	56.9	56.2	--	38.3	43.1	43.8
119	55.9	55.8	54.5	54.9	44.1	44.2	45.5	45.1
126	57.2	54.7	54.2	57.1	42.8	45.3	45.8	42.9
133	55.8	53.7	55.5	56.3	44.2	46.3	44.5	43.7
140	55.8	55.0	57.3	55.5	44.2	45.0	42.7	44.5
147	57.3	54.5	56.3	54.9	42.7	45.5	43.7	45.1
AVG.	58.1	56.4	55.8	56.2	41.9	43.6	44.2	43.8

TABLE 59

CELLULOSE DESTRUCTION AND KINETIC DATA FOR THE DIGESTION OF A MIXTURE OF "SYNTHETIC" REFUSE AND SEWAGE SLUDGE

Day	Unit 2, $\theta = 30$				Unit 1, $\theta = 20$				Unit 3, $\theta = 15$				Unit 4, $\theta = 30$			
	X_1 mg/ℓ	S_0 mg/ℓ	S_1 mg/ℓ	E %	X_1 mg/ℓ	S_0 mg/ℓ	S_1 mg/ℓ	E %	X_1 mg/ℓ	S_0 mg/ℓ	S_1 mg/ℓ	E %	X_1 mg/ℓ	S_0 mg/ℓ	S_1 mg/ℓ	E %
36		31,640	12,000	62.2		31,640	10,000	68.4		31,640	11,500	63.7		63,280	12,900	79.6
43		31,640	10,300	67.5		31,640	10,400	67.2		31,640	12,000	62.0		63,280	14,400	77.3
50		31,640	10,300	67.5		31,640	10,500	66.8		31,640	11,200	64.6		63,280	15,500	75.5
57		31,640	12,100	61.8		31,640	11,300	64.6		31,640	12,400	60.9		63,280	17,000	73.1
64		31,640	11,600	63.4		31,640	12,300	61.2		31,640	13,000	59.0		63,280	17,800	71.9
71		31,640	12,100	61.8		31,640	11,100	65.0		31,640	13,300	58.0		63,280	19,500	69.2
78		31,640	10,400	67.2		31,640	11,100	65.0		31,640	13,100	58.6		63,280	17,800	71.9
85	370	31,640	9,900	68.7	342	31,640	11,400	64.0	393	31,640	12,900	59.3	554	63,280	18,900	70.1
92	419	31,640	11,000	65.2	383	31,640	12,700	59.9	381	31,640	13,100	58.6	624	63,280	17,400	72.5
99	406	31,640	11,500	63.7	439	31,640	14,000	55.8	455	31,640	14,600	53.9	745	63,280	20,000	68.4
106	401	31,640	12,300	61.1	471	31,640	17,900	43.4	432	31,640	15,200	52.0	710	63,280	22,900	63.9
113	421	31,640	10,600	66.5	484	31,640	16,100	49.1	388	31,640	15,700	50.4	750	63,280	23,800	62.4
120	406	31,640	10,300	67.5	449	31,640	16,200	48.8	401	31,640	14,100	55.5	695	63,280	22,000	65.2
127	356	31,640	11,200	64.6	328	31,640	14,800	53.3	417	31,640	13,900	56.0	574	63,280	23,100	63.5
134	330	31,640	12,300	61.1	364	31,640	15,200	52.0	319	31,640	14,600	53.9	560	63,280	25,400	59.9
141	392	31,640	12,400	60.8	386	31,640	15,500	51.0	370	31,640	15,100	52.3	621	63,280	26.400	58.3
148	347	31,640	11,900	52.4	333	31,640	13,900	56.0	330	31,640	14,800	53.2	682	63,280	24,700	61.0
155	344	31,640	12,000	62.1	333	31,640	14,000	55.8	322	31,640	14,600	53.9	650	63,280	25,000	60.5
AVG.[a]	382	31,640	11,550	63.5	397	31,640	15,030	52.5	382	31,640	14,570	54.0	661	63,280	23,070	63.5

[a] Averaged at steady state, day 92 - 155.

X_1 = Viable cells in digester, moss measured as organic Nitrogen, mg/ℓ.

S_0 = Cellulose in influent, mg/ℓ.

S_1 = Cellulose in effluent, mg/ℓ.

E = Cellulose Destruction Efficiency, %.

θ = Detention time, days.

used in arriving at removal rates and then to cellulose destruction efficiencies. The range of efficiencies was from 63.5% for a 30-day detention period to 52.5% and 54% for periods shorter than 30 days.

The cellulose removal rate, q, for each unit was calculated with the use of Equation 1,

$$q = \frac{So - S_1}{X_1\ \theta} \ .$$

Average removal rates proved to be as follows:

Unit No.	$q\left(\frac{\text{mg cellulose removed}}{\text{mg active cells} \cdot \text{days}}\right)$
1	2.092
2	1.753
3	2.979
4	2.027

A significant comparison of removal rates may be made between units 3 and 4, which were loaded equally on an organic basis, but had differing hydraulic loadings. It is evident from the comparison that the superior method for accelerating digestion is by increasing hydraulic loading, rather than by stepping up organic loading concentration. This may be due to a difference in physiological condition of the active organism in the two digesters. Judging from the results for units 1, 2, and 3, it would seem that improvement in removal rate occurs as residence time decreases. However, the permissible increase in hydraulic loading rate does have a maximum limit.

The decomposition rate of cellulose may be determined from Equations 9, 10, and 11 given in the section on theoretical considerations, namely:

$$q = \frac{q_{max} \cdot S}{K_s + S} = \frac{F}{V} \cdot \frac{So - S_1}{X_1} = \frac{1}{\theta} \cdot \frac{So - S_1}{X_1}$$

Therefore, by knowing the flow rate (F), the volume of the digester (V), the influent cellulose concentration (S_o), the effluent cellulose concentration (S_1), and the cells concentration as represented by the organic nitrogen in the effluent sample (X_1), the cellulose removal rate can be determined. By plotting 1/q against 1/S, q_{max} and K_s can be derived.

The decay rate (k_d), the maximum specific growth rate (μ_{max}), and the yield constant (Y), may be estimated from the cell continuity equation, which is:

$$1/\theta = \mu - k_d$$

or by Equation 14:

$$1/\theta = Y\ q - k_d\ .$$

In the present study, the kinetic constants Y, μ_{max}, k_d, and K_s were calculated from the basic data θ, X_1, S_o, S_1 by means of a linear regression computer programming instead of by using graphical solutions. Steady state conditions were taken to be from day 92 to day 155. During this period the data pertaining to units 1 through 4 were analized; unit 4 was excluded later because it introduced a second variable to the variable detention period, namely, influent substrate concentration.

The computed constants are shown in Table 60 and are as follows:

Yield coefficient, $Y = 0.01798$ mg cells produced/mg cellulose removed;

Maximum specific growth rate, $\mu_{max} = 0.1204\ day^{-1}$;

Specific cell decay rate, $k_d = 0.0084\ day^{-1}$

For practical purposes k_d was small enough to be taken as zero:

Michaelis-Menten constant, $K_s = 28{,}353$ mg cellulose/liter.

K_s refers to the cellulose concentration in the digester at one-half the maximum cellulose removal rate.

Computing from μ_{max}, the maximum substrate removal rate ($q_{max} = \mu_{max}/Y$) was 6.70 mg cellulose removed/mg active cells/day.

The cell minimum doubling time, G, was calculated with the use of Equation 16 and based on maximum specific growth rate, μ_{max}. It was:

$$G = \frac{\ln 2}{\mu_{max}} = \frac{0.693}{0.1204} = 5.8 \text{ days} \quad .$$

Therefore, the minimum doubling time for units 1, 2, and 3 was 5.8 days. (Doubling time equals cell generation time only when growth occurs by binary fission.) Minimum doubling time is not the minimum residence time for the operation of a digester because it does not take into account the hydraulic flushing out of the microbial population. Safe operation requires a residence time equal to the washout residence time of the active organisms. The washout residence time, θ_w, was determined from the maximum specific growth rate through the application of Equation 15 as follows:

$$\frac{1}{\theta} = Y\, q_{max} - k_d = (0.01798 \times 6.70) - (-0.0084) = 0.1279$$

$$\theta_w = \frac{1}{0.1279} = 7.8 \text{ days} \quad .$$

This residence time of 7.8 days was optimal for the system.

Discussion

The generation time and washout residence time of the active organisms in this system were 2 to 3 times larger than those found to be applicable in Chan's study of the rate of hydraulysis of cellulose [23]. One reason for this difference was that Chan used only Kraft paper pulp as a cellulose source: whereas, 37.4% of the cellulose fed to the system described herein was in the form of newsprint — a material which is far less degradable than Kraft paper. The net effect of this input, however, can be calculated and only accounts for a 20% loss in rate of hydrolysis.

A more important consideration is the lack of available nitrogen in the feed. Dubos [24] studied the environmental factors affecting the development of cellulose-decomposing bacteria and fungi by adding only cellulose in one test, and adding both cellulose and $(NH_4)_2SO_4$ in another test. The influence of available nitrogen in the latter test increased the efficiency of cellulose decomposition from 55% without nitrogen to 96% with nitrogen. Applying these results to the study described herein suggests that the sluggishness of the organisms, developed on a feed containing only 7.4% sewage sludge, may be attributable at least in part to a lack of available nitrogen.

TABLE 60

KINETIC CONSTANTS FOR THE RATE OF ANAEROBIC DECOMPOSITION OF THE CELLULOSE IN REFUSE

Data Points	Y Yield Constant mg X_1 Prod. per mg Cellulose Decomposed	k_d Decay Rate day^{-1}	r Correl. Coeff.	P Level of Signif.	K_s M-M Const. mg/ℓ	μ_{max} Max. Spec. Growth Rate day^{-1}	r Correl. Coeff.	P Level of Signif.	q_{max} Max. Decomp. Rate day^{-1}	G Cell Doubling Time days	θ_w Cell Washout Time days
40 Includes Unit 4	0.019	-0.003	0.784	0.01	1,207	0.044	0.080	0.5	2.32	15.7	22.7
30 Excludes Unit 4	0.018	-0.008	0.825	0.01	28,353	0.120	0.368	0.05	6.70	5.8	7.8

The K_0 value was usually high, as compared to constants reported for other biological systems. However, it should be pointed out only soluble substrates rather than the particulate substrate reported herein were used in the reported systems. The difference in nature of the substrate is an important distinction, since the value of K_s is obtained in terms of the total concentration of linkages in the substrate. The fact that this was an enzyme-catalyzed system means that accessibility of linkages to attack is a factor. For a soluble substrate accessibility is no problem, but for particulate matter only those linkages exposed to the enzyme would influence the rate of formation of the enzyme-substrate complex.

The statistical analysis indicates a satisfactory correlation for Y and k_d regardless of whether or not the data from unit 4 are included. However, only the data from units 1, 2, and 3 meet the 5% test for level of significance for K_s and μ_{max}. Although the correlation is not good, it may be considered acceptable for a system operated on a substrate containing a variable ingredient such as sewage sludge.

A comparison was made to determine whether or not this is a growth-associated system. In Figure 8 the net growth rate, $1/\theta$, is plotted as a function of the cellulose removal rate, q, and the gas production rate. The fact that both gas production and substrate removal increase as the net growth rate increases, and that the curves have similar slopes, indicates that this is indeed a growth-associated process, as one would expect.

Solids Reduction

The usual procedure for computing solids reduction gives misleading results when applied to this study. This is shown by the apparent magnitude of solids reduction indicated in Table 61. The percentage removals declined as hydraulic loading was increased. However, percentage removals were calculated from organic loading concentration, and do not account for improved efficiency from increases in hydraulic loading. For example, unit 3 received twice the hydraulic load of unit 2, yet the influent solids concentration (g/mℓ) was equal in both units. On this basis it is not surprising that the solids concentration in the effluent from unit 3 was somewhat greater than that from unit 2. As shown in the preceding section on kinetics, the removal rate was much greater in unit 3 than in unit 2.

A more striking example of the impact of removal rate is given by the data in Table 62, in which is given the residual solids concentration in each unit. A comparison of the data pertaining to unit 3 with those for unit 4 will show that unit 4 had a residual solids concentration nearly twice as great as did unit 3. This underscores the difference in efficiency of the two units, even though they appear to have equal percentage solids removals as indicated in Table 61.

The efficiency of the units in terms of gas produced per pound of volatilie solids added or destroyed is shown by the data listed in Table 63. The efficiency of the cultures in units 2 and 4, both on a 30-day detention period, were identical, namely, 6.2% on the basis of solids added.

Of particular interest is the fact that the culture in unit 4 was about 10% more efficient that that in unit 3 when evaluated on the basis of the applied measures of performance. Yet in terms of solids removal, the reverse was true. These two differences demonstrate that a longer detention time favors gas production, while a shorter detention time favors substrate hydrolysis.

Efficiency of Digestion of the "Synthetic" Wastes

Only units 2 and 4 may be validly compared to the sludge (control) digester with respect to efficiency since these were the only digesters operated on a 30-day detention period. The computed efficiency of both digesters was 60.6%. The cellulose destruction efficiency of the synthetic refuse component for unit 2 was 62.8%; and that for unit 4, 62.7%.

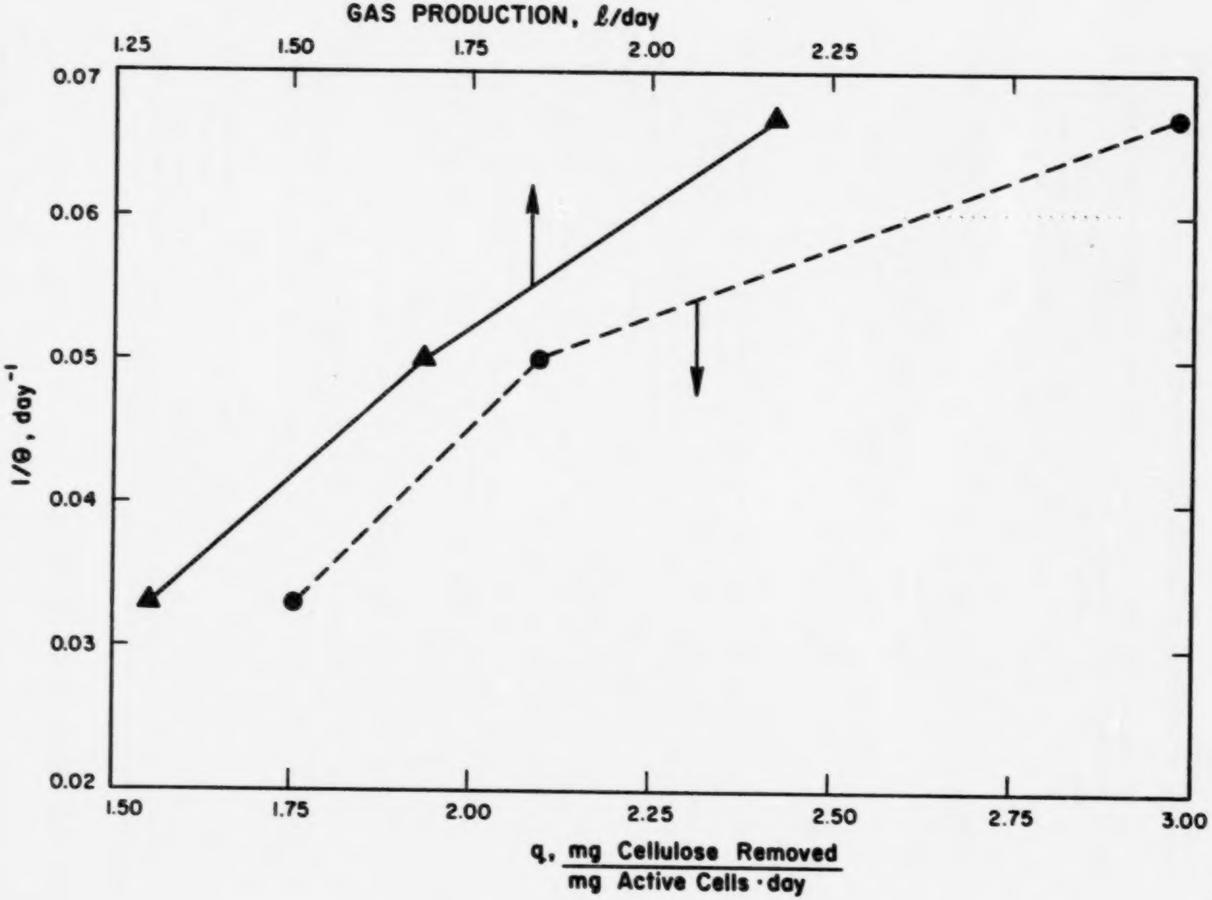


FIGURE 8. GROWTH ASSOCIATED PLOT

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TABLE 61

PERCENTAGE REDUCTION OF SOLIDS IN THE DIGESTION OF "SYNTHETIC" REFUSE

Day	Unit 2 30-day detention time		Unit 1 20-day detention time		Unit 3 15-day detention time		Unit 4 30-day detention time double loading	
	Total	Volatile	Total	Volatile	Total	Volatile	Total	Volatile
19	71.1	77.0						
26	69.0	74.5						
33	73.6	79.8						
40	66.0	71.2	58.7	65.5	45.7	64.0	74.8	83.0
47	64.6	69.6	52.1	58.0	48.8	54.0	62.2	69.1
54	60.5	65.1	49.8	55.5	37.3	41.4	55.8	62.0
61	66.0	71.2	65.1	72.4	46.5	65.0	61.2	68.0
68	69.2	75.0	66.2	73.6	54.0	60.0	68.3	75.8
75	64.8	70.0	71.9	80.0	46.1	51.1	54.3	60.3
82	65.8	71.0	70.8	78.9	44.5	62.8	55.0	61.0
89	61.4	66.1	70.5	78.5	43.9	48.8	53.5	59.5
96	62.9	67.9	70.5	75.5	51.2	56.8	50.0	55.5
103	62.9	67.8	65.7	73.2	41.2	45.7	52.2	58.0
110	63.3	68.4	59.9	66.7	50.0	55.5	50.0	55.5
117	55.0	59.1	56.1	62.5	37.1	41.3	44.5	49.4
124	59.2	63.9	56.1	62.5	44.5	49.4	48.3	53.7
131	51.7	55.5	55.7	62.0	41.3	45.8	43.0	47.8
138	49.3	52.6	48.9	54.5	48.5	53.7	29.1	32.3
145	58.7	63.2	52.5	58.4	43.5	48.1	39.0	43.2
152	53.6	57.5	56.8	63.3	47.5	52.6	40.2	44.7
AVG.	62.3	67.3	60.4	67.1	45.3	52.7	51.8	57.6

TABLE 62

SOLIDS CONCENTRATION IN THE EFFLUENT OF DIGESTERS RECEIVING A "SYNTHETIC" REFUSE AND SEWAGE SLUDGE

Day	Unit 2 $\theta = 30$		Unit 1 $\theta = 20$		Unit 3 $\theta = 15$		Unit 4 $\theta = 30$ Double Loading	
	Total	Volatile	Total	Volatile	Total	Volatile	Total	Volatile
19	3.07	2.08	2.12	1.40	2.50	1.71	3.49	1.90
26	2.89	1.97	1.98	1.40	2.40	1.78	3.11	1.98
33	2.63	1.77	1.98	1.37	2.36	1.72	3.28	2.15
40	2.56	1.84	1.92	1.46	2.11	1.62	3.29	2.31
47	2.42	1.77	1.90	1.50	2.06	1.66	3.22	2.38
54	2.38	1.80	1.88	1.50	2.05	1.72	3.62	2.80
61	2.37	1.70	2.11	1.50	2.16	1.64	3.57	2.64
68	2.42	1.68	2.40	1.69	2.17	1.70	4.05	2.77
75	2.14	1.56	2.45	1.57	2.12	1.73	3.47	2.67
82	2.19	1.59	2.69	1.76	2.13	1.64	3.50	2.73
89	2.05	1.54	2.69	1.77	2.16	1.78	3.40	2.66
96	2.00	1.48	2.80	1.93	2.21	1.76	3.41	2.74
103	2.09	1.57	2.99	2.12	2.32	1.93	3.84	3.06
110	2.15	1.59	2.88	2.16	2.40	1.92	3.90	3.12
117	2.09	1.64	2.80	2.16	2.46	2.07	4.03	3.30
124	2.24	1.72	2.77	2.14	2.42	1.99	4.11	3.31
131	2.27	1.81	2.64	2.04	2.45	2.03	4.34	3.57
138	2.25	1.82	2.53	2.03	2.47	1.99	4.23	3.64
145	2.19	1.68	2.43	1.92	2.32	1.91	4.12	3.44
152	2.14	1.70	2.32	1.78	2.30	1.86	4.01	3.34
AVG.	2.20	1.66	2.56	1.87	2.28	1.84	3.84	3.05

Steady state average day 54 - 152

TABLE 63

EFFICIENCY OF THE DIGESTION OF THE "SYNTHETIC" REFUSE

Day	Unit 2 (30 day detention time)			Unit 1 (20 day detention time)			Unit 3 (15 day detention time)			Unit 4 (30 day detention time) (double-loading)		
	Gas cu ft/day	cu ft/lb Added	cu ft/lb Destr.	Gas cu ft/day	cu ft/lb Added	cu ft/lb Destr.	Gas cu ft/day	cu ft/lb Added	cu ft/lb Destr.	Gas cu ft/day	cu ft/lb Added	cu ft/lb Destr.
19	0.0520	6.4	8.3	0.0957			0.0870			0.0650		
26	0.0570	7.0	9.4	0.0820			0.0990			0.0823		
33	0.0484	5.9	7.5	0.0773			0.1160			0.0975		
40	0.0582	7.1	10.1	0.0817	6.7	10.2	0.1073	6.6	10.3	0.1150	7.1	8.5
47	0.0530	6.5	9.4	0.0780	6.4	11.0	0.1030	6.3	11.7	0.1094	6.7	9.8
54	0.0454	5.6	8.6	0.0800	6.6	11.8	0.1028	6.3	15.3	0.1100	6.7	10.9
61	0.0462	5.7	8.0	0.0522	4.3	5.9	0.0958	5.9	9.0	0.1171	7.2	10.6
68	0.0573	7.0	9.4	0.0253[a]	2.1[a]	2.8[a]	0.0961	5.9	9.9	0.1330	8.2	10.8
75	0.0573	7.0	10.0	0.0222[a]	1.8[a]	2.3[a]	0.0920	5.7	11.1	0.1120	6.9	11.4
82	0.0502	6.2	8.7	0.0574	4.7	6.0	0.0862	5.3	8.5	0.1215	7.5	12.2
89	0.0516	6.3	9.6	0.0581	4.8	6.1	0.0884	5.4	11.1	0.1050	6.5	10.8
96	0.0526	6.4	9.5	0.0535	4.4	5.8	0.0810	5.0	8.7	0.0960	5.9	10.6
103	0.0529	6.5	9.6	0.0539	4.4	6.0	0.0785	4.8	10.5	0.0820	5.0	8.7
110	0.0492	6.0	8.8	0.0478	3.9	5.9	0.0710	4.4	7.8	0.0767	4.7	8.5
117	0.0511	6.3	10.6	0.0524	4.3	6.9	0.0519	3.2	7.7	0.0776	4.8	9.6
124	0.0332	4.1	6.4	0.0362	3.0	4.8	0.0591	3.6	7.3	0.0604	3.7	6.9
131	0.0541	6.6	12.0	0.0708	5.8	9.3	0.0877	5.4	11.7	0.0920	5.6	11.8
138	0.0500	6.1	11.7	0.0702	5.8	10.5	0.0834	5.1	9.5	0.0926	5.7	17.6
145	0.0431	5.3	8.4	0.0715	5.9	10.0	0.0887	5.4	11.3	0.1010	6.2	14.3
152	0.0420	5.1	9.0	0.0652	5.4	8.4	0.0873	5.4	10.1	0.1170	7.2	16.1
AVG.	0.0502	6.2	9.25	0.0658	5.1	7.3	0.0881	5.3	10.1	0.0982	6.2	11.1

[a] Omit from average, because not typical of normally functioning unit.

The results are summarized for each parameter in Table 64. A summary of the kinetic constants derived for units 1, 2, and 3 is given at the bottom of the table.

DISCUSSION

The laboratory phase of the studies on the anaerobic digestion of solid wastes was initiated over three years ago, and was completed about three months prior to the writing of this report. In this section of the report is given a brief summary of results obtained to date, as well as a brief evaluation of their relevance to the objectives of solid wastes management.

The laboratory-scale investigations were divided into three categories; namely, 1) those concerned with the digestion of urban organic wastes in combination with sewage sludge; 2) those dealing with the kinetics of solid waste digestion; and 3) those pertaining to the digestion of organic solid wastes in combination with animal manures. Major findings made in each of these categories of study are summarized in Tables 65, 66, and 67, respectively.

Digestion of Urban Refuse

The data in Table 65 emphasize the efficiency with which the destruction of cellulose is accomplished in the digestion process. As far as refuse is concerned, cellulose is of primary importance, inasmuch as it constitutes approximately 80% of the organic material (dry weight) in urban wastes. It is significant that Kraft paper, which constitutes about 40% of the organic urban wastes, also was the material most readily destroyed in the digesters. A clue to its ease of destruction is that Kraft paper is about 97% cellulose; and of this cellulose, 94% is destroyed in the digestion process. The second largest component of the organic fraction of urban solid wastes is newsprint. It constitutes about 33% of the total organic urban refuse, and of this amount about 50% is destroyed in the digestion process. Thus, paper, a component which accounts for nearly 75% of the dry weight of the organic fraction of urban wastes, can be destroyed to the extent of 82% through anaerobic digestion.

Green garbage, which probably accounts for around 10% of the organic urban refuse in terms of weight, id digested readily. In the experiments, the overall digestion efficiency of digesters receiving nothing but green garbage was approximately 90% that of the control digesters which received only raw sewage sludge. Destruction of the cellulose in this material probably was about 80%. In terms of overall solids and cellulose destruction, garden debris in the form of grass clippings was digested with an efficiency about equal to that with raw sewage sludge. However, gas production efficiency was only about 73% of that with sewage sludge. Wood proved to be almost immune to the digestion process. On the other hand it does not exert any inhibitory effect on the process.

A combination of a composit ("synthetic") refuse consisting of the materials discussed in the preceding paragraphs and of raw sewage sludge digested quite well, provided the alkalinity was kept at an appropriate level. The proportions of refuse and sludge were those to be expected when organic refuse routinely ground into the sewers and digested along with the sewage sludge. Inasmuch as the nitrogen content of this combination of refuse and sludge was less than optimum (C:N, 48:1), the pH of the culture had a tendency to be lower than desired. This tendency was corrected by increasing the alkalinity of the culture through the addition of $Ca(OH)_2$.

Judging from the results obtained in the studies, any combination of sludge and paper fed a digester should be at a maximum about 60% paper. In practice this would mean that about 80% of the paper in the waste stream could be digested. The remaining 20% would have to be diverted. However, in practice, especially in the not-too-distant future, it is highly unlikely that 80% of the paper entering the waste stream will be destined for destruction. On the contrary, the increasing

TABLE 64

SUMMARY OF THE RESULTS PERTAINING TO THE DIGESTION OF THE "SYNTHETIC" REFUSE

Parameter	Unit 2 θ = 30 days	Unit 1 θ = 20 days	Unit 3 θ = 15 days	Unit 4 Double Organic Loading θ = 30 days
$\frac{\text{cu ft Gas Produced}}{\text{lb Vol. Sol. Added}}$	6.2	5.1	5.3	6.2
$\frac{\text{cu ft Gas Produced}}{\text{lb Vol. Sol. Destroyed}}$	9.3	7.3	10.1	11.1
Volatile Solids Reduction, %	67.3	67.1	52.7	57.6
Total Solids Reduction, %	62.3	60.4	45.3	51.8
Cellulose Destruction, %	63.5	52.5	54.0	63.5
Methane, %	58.1	56.4	55.8	56.2
CO_2, %	41.9	43.6	44.2	43.8
pH	7.18	7.07	7.00	7.02
Volatile Acids mg/ℓ as acetic	33	339	62	63
Alkalinity mg/ℓ as $CaCO_3$	2696	2521	2281	2764
Alkalinity Added mg/ℓ/week	567	750	978	513

Kinetic Constants for Units 1, 2, 3

Yield Coefficient, Y = 0.01798 $\frac{\text{mg cells produced}}{\text{mg cellulose removed}}$

Specific Cell Decay Rate, K_d = 0.0084 day^{-1}

Correlation Coefficient, r = 82.50%

Michaelis-Menten Constant, K_s = 28353 mg cellulose per liter

Maximum Specific Growth Rate, μ_{max} = 0.1204 day^{-1}

Maximum Substrate Removal Rate, q_{max} = 6.70 $\frac{\text{mg cellulose removed}}{\text{mg active cells} \cdot \text{day}}$

Cell Doubling Time, G = 5.8 days

Cell Washout Time, θ_w = 7.8 days

TABLE 65

SUMMARY OF DIGESTER EFFICIENCIES WITH RESPECT TO URBAN ORGANIC SOLID WASTES

Urban Organic Wastes			Cellulose Destruction Efficiency (%)	Gas Production Efficiency	
Component	Dry Weight			Gas Produced Per Volatile Solids Added (cu ft/lb)	Waste Compared to Sewage Sludge (%)
	(lb/capita/day)	(% of Total)			
Sewage Sludge	0.120	7.4	80	9.6	100
Green Garbage	0.175	10.8	(80)	8.8	90.7
Kraft Paper	0.642	39.5	93.5	9.0	94.9
Newspaper	0.534	32.9	49.6	5.2	53.5
Garden Debris (As Grass Clippings)	0.089	5.5	78.5	6.6	73.1
Wood (As White Fir)	0.063	3.9	--	0.4	4.4
Composite of Above (Based on percent generated)	1.623	100	64.4	6.0	62.6

TABLE 66

SUMMARY OF RESULTS OF STUDIES ON THE KINETICS OF DIGESTION

Residence Time, θ (days)	[a]Active Cells Conc., x_1 (mg/ℓ)	[b]Cellulose Concentration		Efficiency Cellulose Destruction (%)	Cellulose Removal Rate, q $q = \frac{S_0 - S_1}{x_1 \theta}$
		Influent	Effluent		
		S_0 (mg/ℓ)	S_1 (mg/ℓ)		
30	382	31,640	11,550	63.5	1.753
20	397	31,640	15,030	52.5	2.092
15	382	31,640	14,570	54.0	2.979

[a]Active cells measured as organic nitrogen concentration.

[b]Comprises over 80% of substrate concentration.

Kinetic Constants Computed from Basic Data

(From Michaelis-Menten, $q = \frac{q_{max} \cdot S}{K_s + s}$ and Cell Continuity, $\frac{1}{\theta_c} = Yq - K_d$)

Yield Coefficient, $Y = 0.01798$ mg cells produced per mg cellulose removed.

Specific Cell Decay Rate, $K_d = 0.0084$ day^{-1}.

Correlation Coefficient, $r = 82.50\%$.

Level of Significance, $P = 0.01$.

Michaelis-Menten Constant, $K_s = 28,353$ mg cellulose per liter.

Maximum Specific Growth Rate, $\mu_{max} = 0.1204$ day^{-1}.

Correlation Coefficient, $r = 36.80\%$.

Level of Significance, $P = 0.05$.

Maximum Substrate Removal Rate, $q_{max} = \frac{\mu_{max}}{Y} = 6.70 \ \frac{\text{mg cellulose removed}}{\text{mg active cells-day}}$

Cell Doubling Time, $G = \frac{\ln 2}{\mu_{max}} = 5.8$ days.

Cell Washout Time $\theta_w = \frac{1}{Y\,q_{max} - K_d} = 7.8$ days.

TABLE 67

SUMMARY OF RESULTS OF STUDIES ON THE DIGESTION OF ORGANIC REFUSE COMPONENT AND ANIMAL MANURE COMBINATIONS

Component	Loading Proportion (%)	Cellulose Destruction (%)	[a]Solids Destruction, %		Efficiency		Methane Content of Gas, %
			Total	Volatile	cu ft Gas per lb VS Added	Compared to Control, %	
Chicken Manure	100	--	57.7	67.5	5.0	53.2	59.8
(Chicken Manure Paper Pulp) C:N = 70:1	30.8 69.2	91.9	69.6	76.8	7.8	80.5	60.0
(Chicken Manure Newspaper)	50 50	46.7	39.1	45.3	4.1	45.6	66.1
(Chicken Manure Grass Clippings)	50 50	70.5	50.6	61.1	5.9	65.5	68.1
Steer Manure	100	--	22.1	27.9	1.4	14.9	65.2
(Steer Manure Grass Clippings)	50 50	--	35.6	46.9	4.3	45.7	51.1

[a] Calculated as $\frac{\text{In-Out}}{\text{In}}$ x 100 – conventional method unsuitable for material with a high fixed solids content.

demand for secondary fibers will lend to a constantly increasing demand for recycling paper. More properly, digestion should be reserved for digesting the garbage fraction of refuse and those other organic fractions not amenable to processing for recycling or for which there is no demand. Digestion as a disposal process or step in the disposal process, would be especially compatible with a system involving the hydraulic transport of solid wastes.

Kinetics of Digestion

Results obtained in the kinetic studies on digestion are summarized in Table 66. The medium fed the digesters was the combination of "synthetic" refuse and sewage sludge described in the preceding paragraphs. In addition to learning something about the kinetics of the process, the investigation was aimed at determining the minimum hydraulic residence time at which a digester could be maintained. Detention times of 15, 20, and 30 days were tried. Judging from the results, the rate of removal of cellulose increased with a decrease in detention time within the range of those periods applied in the experiments.

Optimum conditions for operation were characterized by kinetic constants. The constants were computed by means of a linear regression program based on the Michaelis-Menten enzyme catalyzed model and the cell continuity equation. On the basis of the kinetic constants thus derived, the cell doubling time was computed to be 5.8 days; and the cell washout time, 7.8 days. The washout time is the minimum residence time at which a stable bacterial population can be maintained. Although a residence time of 7.8 days seems short in terms of conventional anaerobic digestion practice, unquestionably, a much shorter residence time would be possible under environmental conditions more favorable than those prevailing in the experiments. For example, the "feed" mixture was far from ideal in that the C:N ratio was too high for efficient cellulose destruction. Thus, only 63.5% of the cellulose was destroyed in the experiments; whereas other experiments, in which conditions were more favorable, showed that 80% of the incoming cellulose can be destroyed. Obviously, increasing the rate of cellulose destruction will entail a change in the kinetic description of digestion from that given in the present report. Chan [23], in his work on the kinetics of cellulose fermentation (using an artificial substrate), found that the cell washout time could be as short as 2.86 days. He worked with a carefully formulated substrate consisting of finely divided cellulose powder and soluble nutrients, and maintained his culture under optimum environmental conditions.

Digestion of Organic Refuse and Animal Manure

The utilization of animal manure as a nitrogen source in the digestion process proved to be effective – especially when chicken manure was used as the source. According to the data in Table 67, the efficiency of cultures digesting chicken manure was equal to that of cultures digesting sewage sludge in terms of solids reduction, and about 50% as efficient in terms of gas production. Results obtained in the digestion of combinations of chicken manure and components of refuse lead to the following observations: 1) Chicken manure is readily digested in combination with Kraft paper pulp at C:N ratios as high as 70:1. Solids reduction is satisfactory and over 90% of the introduced cellulose is destroyed. 2) In terms of cellulose destruction and gas production a 1:1 mixture of chicken manure and newspaper could be digested at an efficiency approximately one-half that at which sewage sludge normally is digested. 3) A mixture consisting of equal portions of chicken manure and grass clippings will be digested with an accompanying solids destruction nearly equal to that which takes place in sludge digestion. Gas production is about two-thirds that which takes place in the digestion of sewage sludge.

As others have found, steer manure remains relatively unchanged in the digestion process, in that only about 25% of the solids are destroyed. Gas production efficiency was only about 15% of that when sewage sludge was digested. A mixture of equal parts of steer manure and grass clippings was digested with a resulting solids destruction about 40% that taking place in sludge digestion. Gas production from the digestion mixture was less than 50% of that from digesting sewage sludge.

Economics of Solid Waste Digestion

According to the economic analysis described in the Second Annual Report, the total per capita annual cost of separating, grinding, and digesting refuse would be $2.18 (1968) for a city of 30,000, $1.27 for a city of 300,000, and $0.75 for a city of 1,000,000. Total costs per ton of refuse digested for the above population levels would be $4.00, $2.32, and $1.42, respectively. If only the garbage fraction of refuse were digested, the per capita costs would be lower than those cited, but higher on a per ton basis because of the lesser volumes involved. A useful by-product of refuse digestion would be the methane produced by the culture.

GENERAL CONCLUSIONS

1. The disposal of the organic fraction of the solid wastes by anaerobic digestion process would be economically feasible provided the costs of dewatering the sludge were reasonable.

2. No inhibition or retardation of an anaerobic culture will occur when solid wastes are combined with sewage sludge as a substrate for digestion. There is an important proviso, however, namely that the nitrogen requirements of the culture are met.

3. A significant reduction in the bulk of the incoming material is accomplished.

4. The advantages inherent in the hydraulic transport of solid wastes may well justify the incorporation of digestion as a disposal method in areas so served.

V. BIOLOGICAL FRACTIONATION OF SOLID WASTES

INTRODUCTION

The research effort of this phase of the technology investigation is concerned with the enzymatic conversion of the cellulosic fraction of solid wastes to glucose or other useful products by microbial action. Previous work as described in the First and Second Annual Reports involved 1) a literature survey of potentially useful microorganisms; 2) a preliminary evaluation of the feasibility of using certain organisms, particularly Sporocytophaga myxococcoides and Myrothecium verrucaria, and 3) construction of a 3-stage fermentation apparatus (14 liters per stage) suitable for batch or continuous operation.

Work during the past year was concerned primarily with two aspects of the problem; namely, laboratory studies involving the fungus Trichoderma viride QM 6a and directly toward improving the yield of the enzyme celluloase; and a process design and economic evaluation of an enzymatic saccharification process based on the fungus.

EXPERIMENTAL STUDIES ON ENZYME PRODUCTION

General Procedure

The experiments were carried on with the use of 14-liter New Brunswick microfermenter units modified to meet the experimental conditions. The internal dimensions of the fermenters are 8.5 in. diameter and 17 in. in height. Arranged in the interior of each unit were four hollow baffles and numerous probes and ports. Each unit was equipped with two 4.625-in. four-blade turbine impellers, one mounted directly above an air sponger; and the other, above the liquid level to aid in breaking up foam. A complete description of the apparatus is given in the Second Annual Report.

The organism used in the experiments was Trichoderma viride QM 6a. The temperature was maintained at 29°C. Aeration was at 0.25 VVM, i.e., at 2 ℓ/min for the 8 liters of medium contained in each unit. The impellers were rotated at 150 rpm. The carbon source was either glucose, cellulose (Solka floc SW40), or both as specified. All fermentations were performed batchwise. The analytical techniques used were as follows:

1. determination of dry weight of culture broth;
2. measurement of reducing sugar concentration;
3. measurement of cellulase enzyme activity; and
4. microscopic examination and contamination tests.

For the dry weight determination, two 10-mℓ samples of culture broth were centrifuged at 5,000 rpm for 5 minutes. The supernatant was saved and the percipitate was washed and recentrifuged. The supernatant from the wash was poured off and the percipitate was dried overnight in a 95°C oven and then weighed. In runs where cellulose was used as a substrate, the dry weight figures were a total of both the cell material and the residual cellulose.

The concentration of glucose or total reducing sugars was measured according to the denitrosalicylic acid (DNS) method [25]. Three mℓ of DNS reagent (see reference for preparation) were added to one mℓ of sample in a large test tube and the resulting mixture was placed in a boiling water bath for exactly 5 minutes. The test tube was then placed in a running tap water cooling bath for approximately 5 minutes. The liquid was then diluted to 25 mℓ with distilled water and the test tube was covered and inverted 4 to 5 times to mix. Absorbance at 600 mμ was measured with the use of a Bechman DU-2 spectrophotometer. Readings were corrected for appropriate reagent and substrate blanks. The reducing sugar concentration measured as glucose was determined from a calibration curve based on glucose standards.

Cellulase enzyme activity was measured by the ability of the enzyme to hydrolyze Whatman No. 1 filter paper under standard conditions. This form of cellulose was chosen for several reasons. It had been used previously by workers [4, 26, 27], and thus would provide a common reference point for comparing results. Secondly, Whatman No. 1 filter paper is readily available and is a highly standardized form of cellulose. Thirdly, and most importantly, its susceptibility to enzymatic hydrolysis is about on a par with that of the forms of cellulose which would be handled in a waste cellulose conversion process. A filter paper (FP) activity unit is defined as the number of milligrams of reducing sugar produced by 1 milliliter of cell-free enzyme solution acting on 50 mg of Whatman No. 1 filter paper (a 1 x 6 cm strip) in 1 mℓ of 0.05 M pH 4.8 Na citrate buffer at 50°C for 1 hour. At the end of 1 hour, 1 mℓ of this hydrolysate is tested for reducing sugar concentration by the DNS method.

Before any of the analyses were performed, a small sample of the culture broth was examined microscopically to detect any visible contaminants, and also to observe the stage of growth of the culture. Also at this time, plates of glucose nutrient agar and potato dextrose agar were streaked and incubated for about one week as a further search for bacterial or fungal contaminants.

Experiment 1. Glucose Substrate with pH Control

An initial experiment was performed to determine the preliminary growth characteristics of *Trichoderma viride* QM 6a on a glucose substrate. The nutrient medium was that developed by Mandels and Weber [28]. The composition was as possible: KH_2PO_4, 2 g/ℓ; (NH_4), SO_4, 4 g/ℓ; urea, 0.3 g/ℓ; $MgSO_4 \cdot 7H_2O$, 0.3 g/ℓ; $CaCl_2$, 0.3 g/ℓ; $FeSO_4 \cdot 7H_2O$, 5 mg/ℓ; $MnSO_4 \cdot 7H_2O$, 1.56 mg/ℓ; $ZnSO_4 \cdot 7H_2O$, 1.4 mg/ℓ; and $CoCl_2$, 2 mg/ℓ. Reagent grade glucose served as the carbon source and was added at a concentration of 10 g/ℓ. The glucose was sterilized separately to prevent the formation of inhibitory products. A silicone antifoam agent (Union Carbide SAG 471) was added in a concentration of 100 mg/ℓ. Difco protease peptone No. 2 was added to boost cellulase production [28]. To facilitate the measurement and addition of trace minerals, a concentrated (200 x) solution was prepared with 950 mℓ distilled water and 50 mℓ concentrated HCl. Distilled water was used in all medium penetration. The pH was adjusted to 5.0 prior to sterilization, but it rose to 5.8 to 6.0 during sterilization. It was adjusted to 5.0 after sterilization.

The inoculum was 100 mℓ of *Trichoderma viride* from a 3- to 4-day old shake flash culture grown on a 1% glucose substrate having the same composition as that of the medium used in the fermenters.

A lag period of several hours usually followed inoculation. The lag was characterized by a rise in pH — probably due to the deamination of the amino acids in the peptone. Drop in glucose concentration and growth of the organism during the first 80 hours are plotted in Figure 9. As the figure indicates, most of the growth occurred during a 10-hour period. Active growth was accompanied by acid production. However, the pH was held at 5.0 by the automatic addition of 1.0 N NaOH. Fifty-seven percent of the glucose was converted into cellular material (dry weight). The cells began to autolyze after maximum growth had been reached.

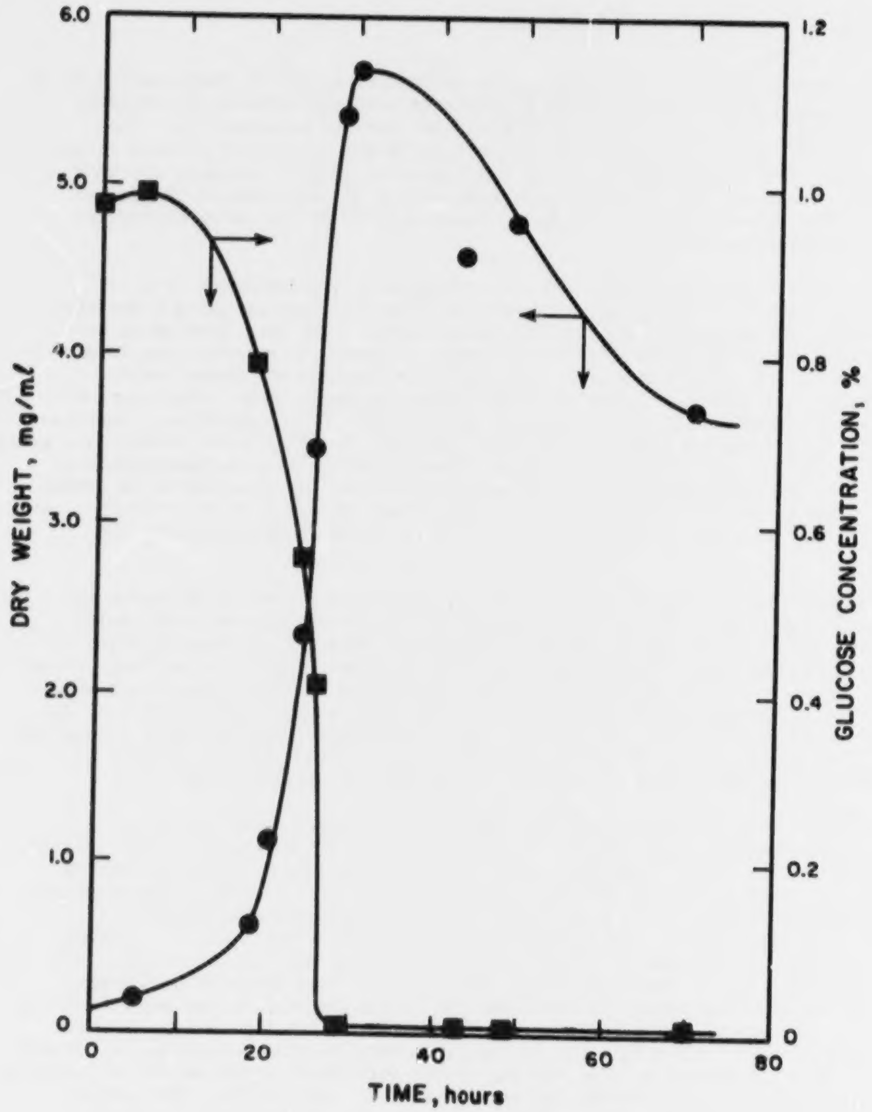

FIGURE 9. GROWTH OF *T. viride* ON GLUCOSE SUBSTRATE WITH pH CONTROL

SW 100

No cellulase activity was observed in the experiments. None was expected since the medium contained no inducing agent. Probably some constitutive cellulases were present, but their concentrations were lower than the sensitivity of the analyses.

Experiment 2. Cellulose Substrate Without pH Control

The next experiment was performed to determine the growth characteristics of *Trichoderma viride* QM 6a when grown on a cellulose substrate without pH control. The nutrient medium was basically the same as that used in Experiment 1. One modification was the use of cellulose (Solka floc SW 40) instead of glucose as the carbon source. The concentration of the cellulose was 10 g/ℓ. Another was that the inoculum was grown in 100-mℓ shaker flasks with a 1% cellulose, 0.1% glucose substrate. The glucose was added to help promote growth of the spore suspension used for initial incoculation.

Foam production was a very serious problem in all experiments in which cellulose was used as a substrate. Attempts to eliminate foam by using a variety and combination of antifoam agents proved unsuccessful. The most that could be achieved was a temporary reduction in the amount of foam. To maintain the foam at an acceptable level, it was necessary to almost continuously add fresh antifoam agent. Mandels and Weber [28] had the same problem in their work. They eventually settled on the procedure of adding small amounts (0.1%) of polyoxyethylene sorbitan monooleate (Atlas Chemical Tween 80) to their medium. Tween 80 is an emulsifying agent which has the effect of "softening" foam and thereby making it more susceptible to the action of antifoam agents. Their method was tried in the experiments described herein. Although the foam problem was not eliminated, it was held to a workable level. Tween 80 (0.1%) was added to the medium in all runs in which cellulose was the substrate.

Another serious problem encountered was that of the rise in pH during the initial period of growth. This effect, caused by the deamination of amino acids, was also apparent in runs using a glucose substrate. However, in runs in which glucose was the substrate, the pH level began to drop when growth became very active. In runs in which cellulose was the substrate, the rise in pH level had a much more serious effect. Growth almost ceased when the pH level reached 5.8 to 6.0. It was necessary, therefore, during such runs to control the upper limit of pH at 5.0 by the automatic addition of acid. Once active growth began, the pH dropped below 5.0 and the culture proceeded to grow without any artificial control of pH.

In Figures 10 and 11 are plotted change in pH, growth, and change in cellulose concentration during an 11- to 12-day period. As the curves show, active growth proceeded until the pH dropped below 3.0, at which point the growth ceased and the filter paper activity* reached a maximum of 0.6 to 0.8 units. The cessation of growth occurred after 4 to 5 days time. In similar experiments, Mandels and Weber [28] obtained a filter paper activity of about 1.00 after 5-6 days. However, they did not have the problem of growth inhibition during the initial pH rise, and therefore did not have to add acid during this period. From their data it seems that the pH did not drop below 3.0 until the 5th or 6th day and filter paper activity had risen to its maximum. The difference between the results obtained by them and these results probably was a function of the difference in time before the pH dropped below 3.0. This difference in time was due to the fact that in the present experiments it was necessary to add acid during the early period of cell growth. The gradual decrease in total dry weight of the cultures seems to be due mainly to autolysis which occurred after growth ceased. The effect of pH on enzyme activity was studied by Mandels and Weber [28]. Their results show that the optimum pH is 4.8 and that the enzyme activity is negligible at pH levels lower than 3.0. It is understandable,

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* FP activity defined by Mandels and Weber [28] as the number of mg of reducing sugar (as glucose) produced by 1 mℓ of cell-free culture liquid acting on 50 mg (1 x 6 cm) strip of Whatman No. 1 filter paper in 1 mℓ of pH 4.8 0.05 M Na citrate buffer at 50°C for 1 hour.

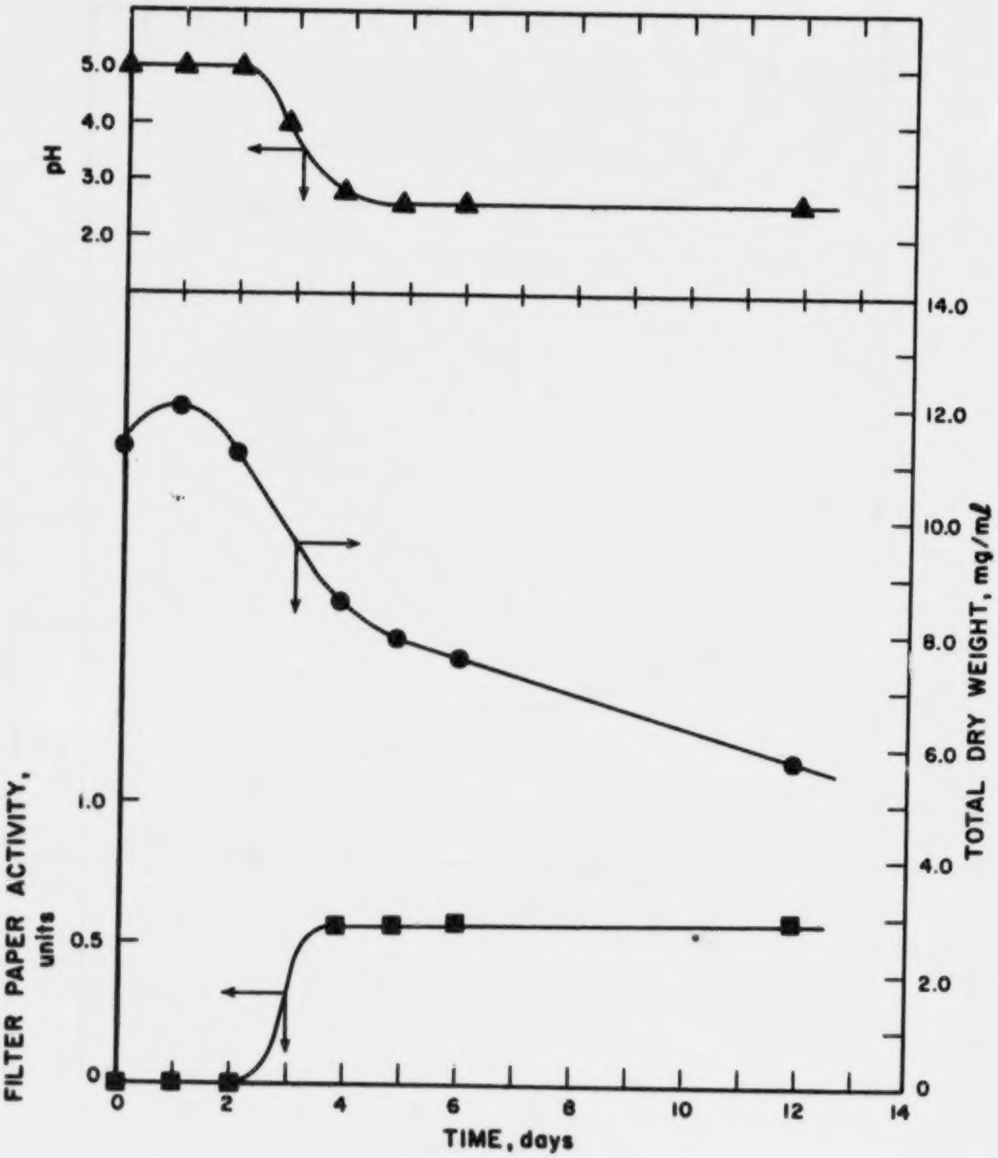

FIGURE 10. GROWTH OF *T. viride* ON GLUCOSE SUBSTRATE WITHOUT pH CONTROL, RUN 1

SW 101

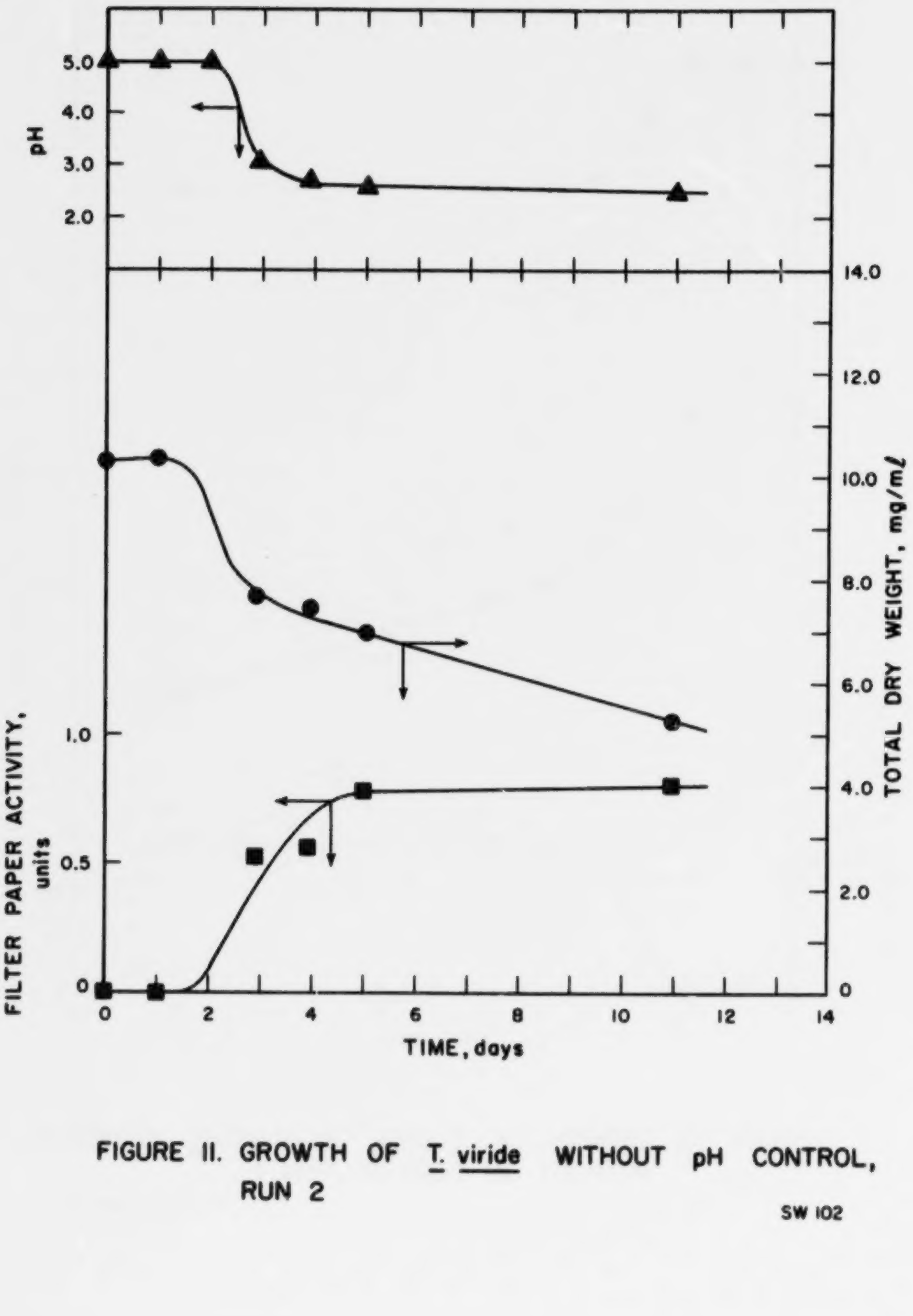

FIGURE II. GROWTH OF T. viride WITHOUT pH CONTROL, RUN 2

SW 102

therefore, that growth of T. viride QM 6a would cease in a culture on a cellulose substrate when the pH drops below 3.0. The reason is that no carbohydrate source is available at pH levels lower than 3, inasmuch as cellulose hydrolysis has come to a standstill.

Experiment 3. Cellulose Substrate with pH Control

The obvious question brought out by the results obtained in the previous experiment is what would happen if pH were controlled. It is possible that with the pH controlled at the optimum for enzyme activity, less enzyme would be produced because less would be needed inasmuch as it is at its maximum activity. On the other hand, it is possible that the rate of enzyme production is related to growth rate, and therefore more enzyme will be produced with the pH held at the optimum for cellulase activity. In this experiment, the aim was to determine the effect of pH control on fungal growth and cellulase activity. The pH of the fungal culture was held at 5.0 by external control and automatic addition of acid and base. Amount of growth and change in cellulose concentration during the first 7 or 8 days are shown in Figures 12 and 13. As would be expected, growth and cellulose degradation both proceeded to a far greater extent than in noncontrolled pH runs. The most interesting aspect, however, was the level of enzyme activity achieved in the two experimental runs.

In run 1, the activity on filter paper reached a level of about 2.1 units after 5 1/2 days and then began to drop off. Plating of samples from the culture indicated that a fungal contaminant had made its appearance. It steadily increased in number throughout the life of the culture. The enzyme activity level remained constant at the maximum in all other experimental runs, so it is highly probable that this observed decrease was due to the presence of the contaminating fungus in the culture.

Results obtained in run 2 were similar to those of run 1. The only major difference was that the activity on filter paper continued to rise after day 6 and reached a higher maximum level than that of run 1. After 9 days the filter paper activity reached a level of 2.86 units.

These results indicate that the rate of enzype production tends to be growth associated when T. viride QM 6a is grown on a cellulose substrate.

Experiment 4. Isolation of Cell Growth and Enzyme Production

The previous results demonstrated that one of the limiting factors in the rate of cellulase production by T. viride QM 6a was the slow rate of growth of the fungus on cellulose substrates. In the first and second runs of the fourth experiment an attempt was made to increase the overall rate of enzyme production by accelerating the initial growth stage of the fungus. A comparison of the results obtained in the first experiment with those of run 2 of the third experiment indicates the existence of a major difference between the growth rate of a culture growing on glucose and that of one growing on cellulose. Growth was complete in 30 hours when the fungus was grown on glucose; whereas, four or five days were required when the fungus was cultured on a cellulose substrate. (Cellulose substrate depletion was assumed to have occurred when the total dry weight equaled 50% of the original substrate concentration.) A major time advantage could be achieved if this difference in growth rate could be put to use.

Runs 1 and 2 of the fourth experiment were carried out in the following manner: In the initial phase the fungus was cultured on glucose as in run 1. At the point at which glucose became depleted, sterile cellulose (Solka floc SW 40) was added aseptically to the culture liquid to bring the concentration of cellulose to about 1%. At the same time, a fresh supply of nutrients (in the same amounts as supplied previously) was added to the culture to replace the depleted nutrients. Dry weight and filter paper activity were then monitored periodically. Throughout the run the pH was held at 5.0. The results are plotted in Figures 14 and 15. In both

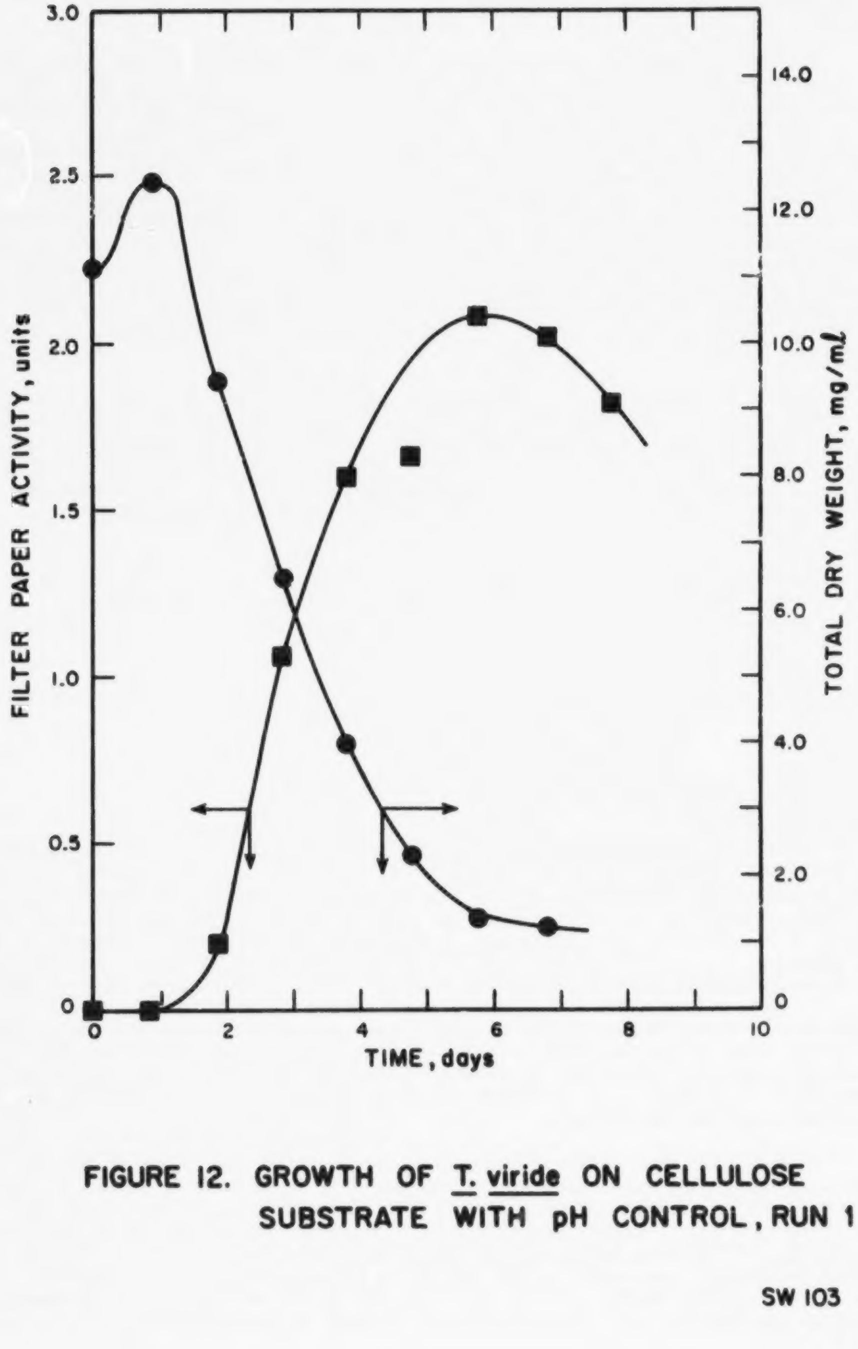

FIGURE 12. GROWTH OF *T. viride* ON CELLULOSE SUBSTRATE WITH pH CONTROL, RUN 1

SW 103

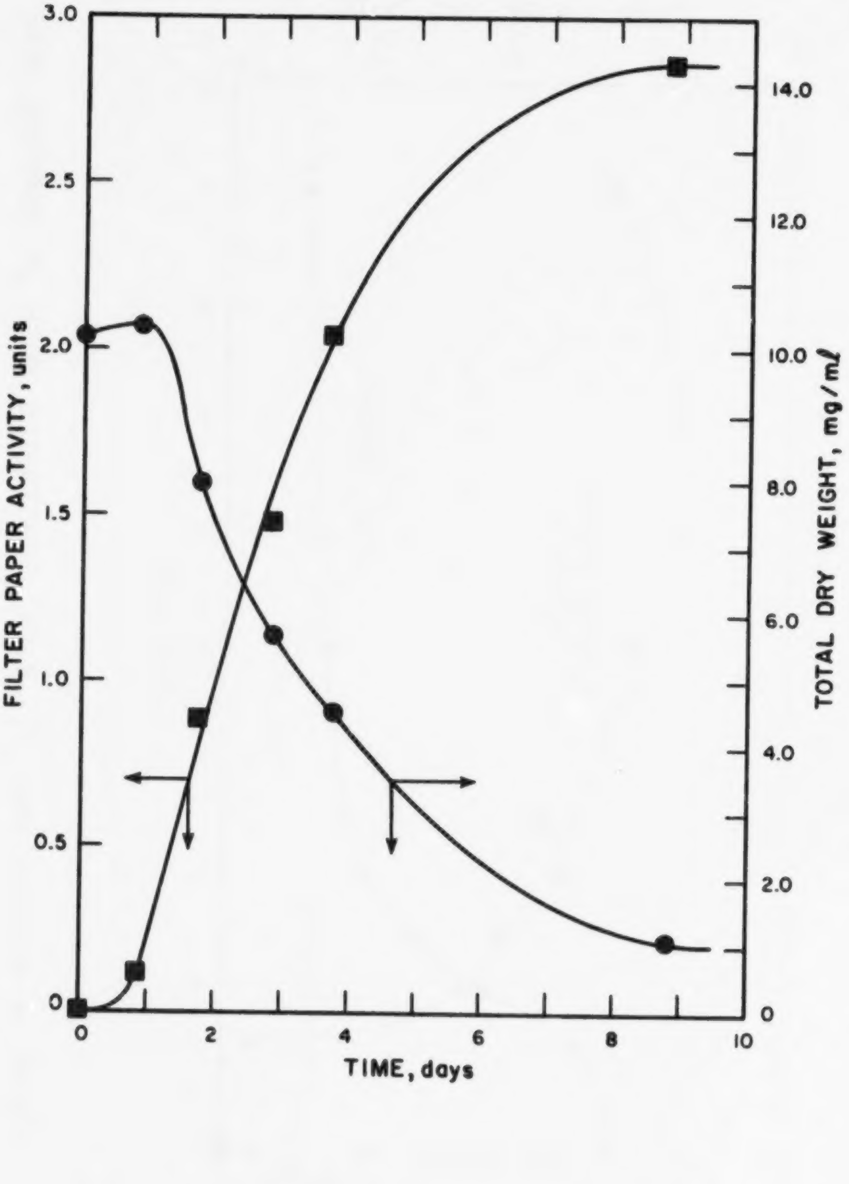

FIGURE 13. GROWTH OF T. viride ON CELLULOSE SUBSTRATE WITH pH CONTROL, RUN 2

SW 104

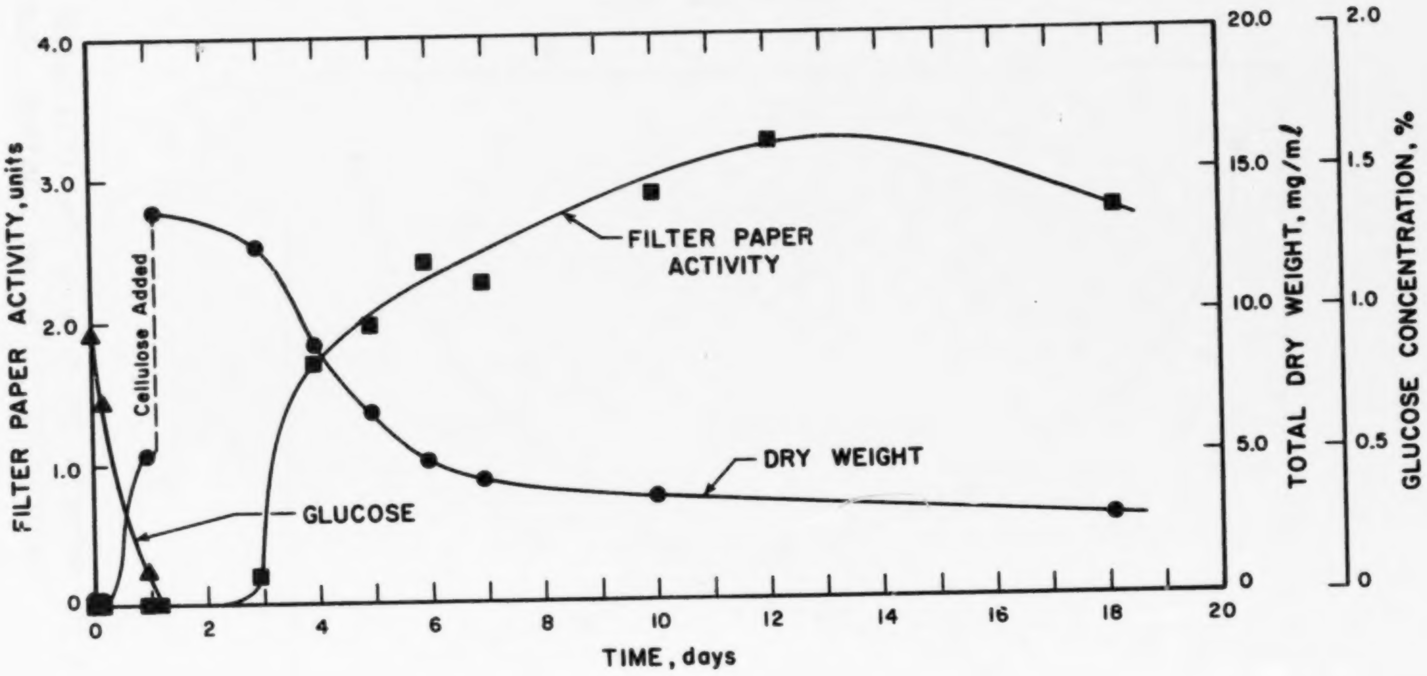

FIGURE 14. GLUCOSE AND CELLULOSE SUBSTRATES WITH pH CONTROL, RUN 1

SW 105

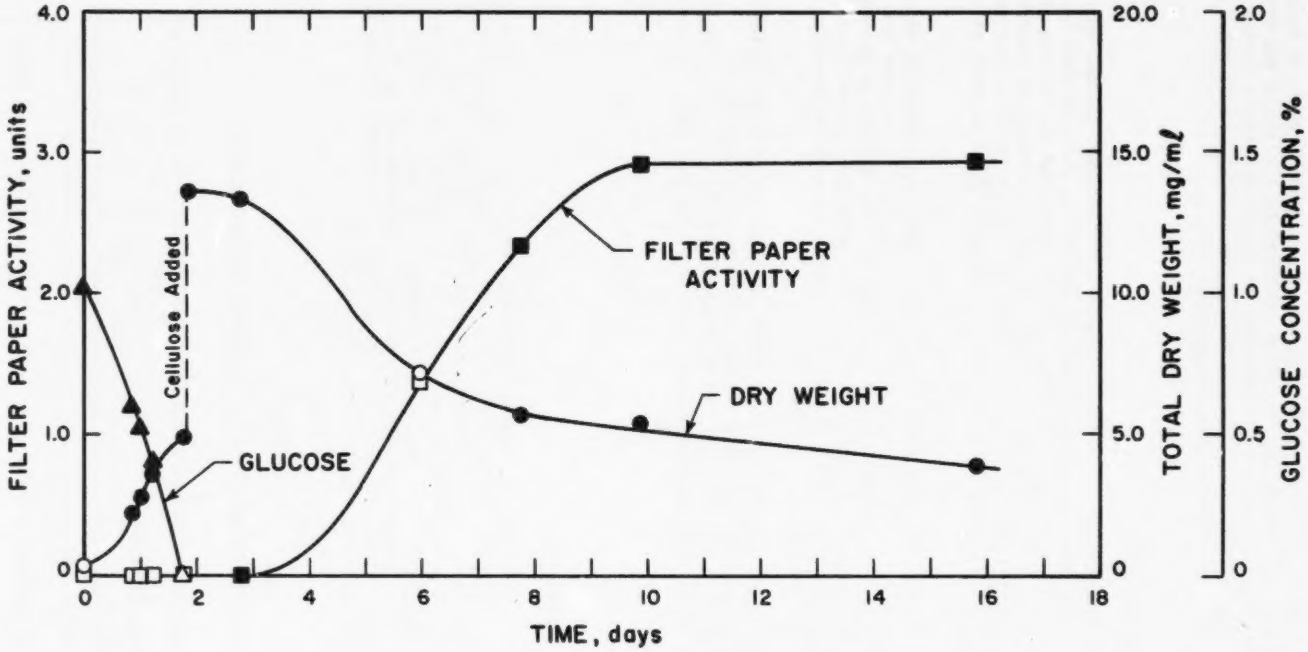

FIGURE 15. GLUCOSE AND CELLULOSE SUBSTRATES WITH pH CONTROL, RUN 2

SW 106

runs two days passed before signs of any cellulase activity appeared in the culture liquid. Following this lag, the cellulase activity rose sharply to high levels. During the 2-day lag period during which the culture was adapting to the cellulose substrate, the carbon source available to the culture was almost completely depleted. It is likely that autolysis of the fungal mycelium occurred to a significant extent during this period, thus accounting for the decrease in total dry weight during the lag period. The advantage of rapid cell growth during the initial period was outweighed by the added time used for the long lag period.

Summary of Experimental Results

In table 68 are summarized the results obtained in the experimental work thus far. The results show that cellulase enzyme production is favored when the pH level is at 5.0 (optimum pH for enzyme activity). It is inhibited at the low pH values (2.5 to 3.0) which occur in the latter stages of growth without pH control. These results suggest that the production of enzyme by T. viride QM 6a is not related to the low pH but rather to the rate of growth of the fungus, which is best at pH 5.0.

The results of the fifth experiment demonstrated that the cellulase enzyme is produced more effectively by first growing the fungus rapidly on glucose and then adding cellulose to induce enzyme synthesis. However, any advantage gained is offset by the long lag phase which takes place before cellulase begins to be metabolized. Therefore, some additional experiments should be done to explore possible techniques to reduce the lag period.

A comparison of this work with that of previous work of Mandels and Weber [28] shows that the enzyme production rate may be increased 150% through pH control. By incorporating pH control with pre-culture on glucose, a very substantial reduction in the plant investment and processing cost could be obtained.

ECONOMIC ANALYSIS

Plant Design and Cost Analysis

To determine in a very general way the economic feasibility of a process involving the hydrolysis of paper wastes to glucose and subsequent production of fungal protein on the glucose, a cost estimate was made for a process such as that diagrammed in Figure 16. The estimate is based on data for growth and hydrolysis rates reported for T. viride QM 6a as reported by Mandels and Weber [28] and by Ghose and Kostick [26, 27]. Apparently the enzyme complex synthesized by T. viride brings about the most rapid saccharification of paper cellulose of any of the enzyme complexes synthesized by any other organism reported thus far.

TABLE 68

ENZYME ACTIVITY IN RELATION TO SUBSTRATE AND pH CONTROL

Culture Conditions	Enzyme Activity At 5 days	(FP units[a]) Maximum
1) Cellulose, no pH control	0.8	0.8 @ 5 days
2) Cellulose, pH control @ 5.0	2.5	2.85 @ 9 days
3) Glucose, cellulose, pH control @ 5.0	2.0	3.12 @ 12 days
4) Mandels and Weber [28], no pH control	1.0	1.86 (semi-continuous)

[a] As defined by Mandels and Weber [28].

The cost estimate was prepared with the additional intention of relating the proportion of capital and operating costs to individual steps in the process. The following evaluation was developed according to a method outlined by Newton and Aries [29].

Description of the Process Design Basis

The raw material for the process is waste cellulose, and the end products are a 5.3% glucose syrup and a mixture of fungal protein and residual cellulose. The glucose solution can be used directly in a secondary fermentation of commercial value or it may be recovered as pure glucose in an additional recovery and purification operation. The protein-cellulose mixture is envisioned as being suited for use as an animal feed or feed supplement.

The basic plant size chosen for the study is based on a daily waste cellulose feed of 10 tons. The amounts of products are estimated to be 18,300 lb of glucose (as 5.3% syrup) and 700 lb/day of dry fungal mycelium-cellulose mixture (80% mycelium). It is envisioned that a plant of this type would be located within a short distance of the source of the waste material. The refuse costs for transportation and rough separation of the cellulosic waste material are not included.

General Process Description

As illustrated in Figure 16, the process consists of the following main steps:

1. Feed Preparation: The nutrient medium is prepared in the medium supply tanks.
2. Cellulose Pretreatment: The cellulose waste as received is reduced in size in a shredder, heat treated at 200°C, and then ground to approximately 50μ diameter particles. The cellulose feed to the fermentor is taken off after the heating; the remainder is ground and fed to the hydrolysis vessel.
3. Microbial Growth and Enzyme Production: In this major step of the process, the growth of *T. viride* QM 6a on cellulose takes place with the simultaneous production of high concentrations of enzyme induced by the presence of cellulose.
4. Separation of Enzyme Solution: In this step the effluent from the fermentor is sent to a rotary drum filter (filter 1) where the fungal mycelium and residual celluose are filtered off from the culture liquid containing the enzyme. The solid mixture is sent to a dryer.
5. Cellulose Hydrolysis (Saccharification): This is the most important step of the process. Here the cellulose enzyme solution produced in step 3 comes in contact with pretreated cellulose waste and a hydrolysis to glucose occurs. Conditions remain aseptic here and growth of the fungus is prevented by the elevated temperature (50°C). According to available data [28], the residence time of the cellulose in this step would be 40 hours for an approximately 50% conversion.
6. Separation of Glucose Solution: The glucose solution is separated from the unhydrolyzed cellulose by filtration (filter 2). The glucose solution (5.3% syrup) is suitable for use in a secondary fermentation or recovery as a solid product in an auxiliary purification operation (not included here). The residual cellulose is dried, reground, and returned to the hydrolysis vessel.

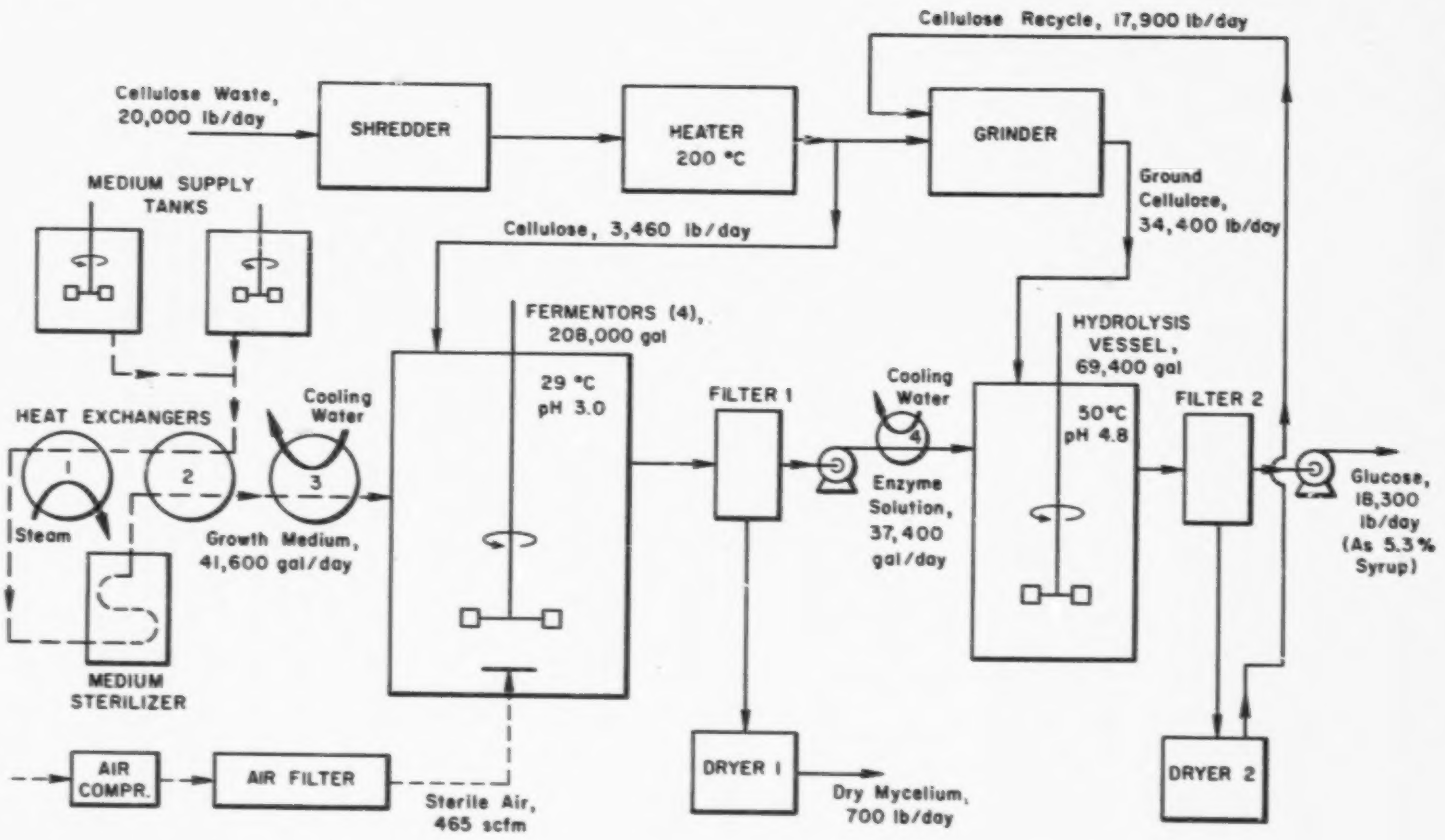
Cellulose Recycle, 17,900 lb/day
Cellulose Waste, 20,000 lb/day
SHREDDER
HEATER 200 °C
GRINDER
Ground Cellulose, 34,400 lb/day
MEDIUM SUPPLY TANKS
Cellulose, 3,460 lb/day
FERMENTORS (4), 208,000 gal
29 °C pH 3.0
HYDROLYSIS VESSEL, 69,400 gal
50 °C pH 4.8
Cooling Water
HEAT EXCHANGERS
1
2
3
4
Steam
Growth Medium, 41,600 gal/day
MEDIUM STERILIZER
FILTER 1
FILTER 2
Enzyme Solution, 37,400 gal/day
Glucose, 18,300 lb/day (As 5.3% Syrup)
AIR COMPR.
AIR FILTER
Sterile Air, 465 scfm
DRYER 1
Dry Mycelium, 700 lb/day
DRYER 2

FIGURE 16. PROCESS FLOW SCHEME FOR THE CONTINUOUS ENZYMATIC SACCHARIFICATION OF CELLULOSE

SW 107

Cost Factors

A capital cost summary for the 10 ton/day plant is presented in Table 69. Table 70 presents a list of costs on 3 bases: cost per day of operation, cost per ton of cellulose treated, and cost per pound of glucose produced. In Table 71 are listed the medium requirements in raw materials as based on a preliminary defined medium [28]. A summary of fixed capital costs is shown in Table 72; it is broken down into the relative costs of four major segments of the process. Major equipment is listed and specified in Table 73. In Table 74 are listed costs for a 10 ton/day plant and a plant capable of handling 100 tons of cellulose per day, based on two methods of scale-up. Also in Table 74 are listed the possible savings from several potential process improvements. It serves to indicate areas of research which should be investigated in order to improve the cost outlook.

It is not surprising that the estimates lead to the conclusion that a 10 ton/day plant is too small for economic operation, due primarily to costs of fixed capital and labor. An increase of size to 100 tons/day capacity [scale-up basis (b)] effects a marked reduction in unit cost and apparently glucose could be produced with a small net gain based on present market value, which assumes a value of $146 for the glucose produced per ton of cellulose converted.

A further reduction in product cost appears possible if certain process improvements can be effected as summarized in part 2 of Table 73. The most important areas of improvement lie in the elimination of the cellulose recycle and increase in fermentation rate or enzyme production rate. Grinding costs do not appear to be excessive. Elimination of the recycle and doubling of the enzyme production rate per unit volume of equipment together could result in a potential savings of $30 per ton of cellulose treated, and a net cost of $79 per ton. Assuming a glucose value of $146 per ton of cellulose, there is a potential profit of $67 per ton. A further potential saving of importance, not assessed in Table 74, is the possibility of using a low cost technical grade simplified medium. A further savings of $10-20 per ton may be possible. Although some savings could be effected by reduction of grinding costs, it does not seem likely that this would be probable.

While it is recognized that the above cost analysis is subject to considerable uncertainty, it may be concluded that processing along these lines appears sufficiently promising to warrant further study.

The increased rate of enzyme production realized during the described experimental work greatly enhances the economic outlook of the proposed process. With pH control, a rate of enzyme production equal to 2.5 times that assumed in the process design appears possible. This suggests a 60% reduction in the fixed capital costs involved in enzyme production (which comprises 52.6% of the total fixed capital costs, as noted in Table 72. In a 100 ton/day plant (see Table 74), this would mean a cost reduction of from $13 to $24 per ton of cellulose processed depending on the method of scale-up. This results in a corresponding net gain of from $17 to $50 per ton of cellulose processed.

TABLE 69

CAPITAL COSTS FOR A TEN-TON CELLULOSE PER DAY "BIOFRACTIONATION" PLANT

Purchased Equipment.	$ 563,275
Equipment Installation	108,530
Piping	200,000
Instrumentation.	22,900
Insulation	28,000
Electrical	38,000
Building	200,000
Land and Yard Improvements	60,000
Utilities.	41,500
Physical Plant Cost.	1,262,205
Engineering and Construction	316,000
Direct Plant Cost.	1,578,205
Contractor's Fee	79,000
Contingency.	316,000
Fixed Capital.	$1,973,205

TABLE 70

MANUFACTURING COSTS FOR A TEN-TON CELLULOSE PER DAY "BIOFRACTIONATION" PLANT

Item	$/day	%	$/ton of Cellulose	$/lb of Glucose
Raw materials (medium)	$ 246.	10.1		
Labor	475.	19.4		
Supervision	70.	2.9		
Maintenance	270.	11.1		
Plant Supplies	41.	1.7		
Utilities[a]	230.	9.5		
Direct Manufacturing Cost	$1332.	54.7	$133.	$0.073
Payroll Overhead	72.	3.0		
Laboratory	72.	3.0		
Plant Overhead	240.	9.9		
Indirect Manufacturing Cost	$ 384.	15.9	$ 38.	$0.021
Depreciation	550.	22.6		
Property Taxes	110.	4.5		
Insurance	55.	2.3		
Fixed Manufacturing Cost	$ 715.	29.4	$ 72.	$0.039
Total Manufacturing Cost	$2431.	100.0	$243.	$0.133

[a] Steam 65%, electricity 31%, other 4%.

TABLE 71

COSTS FOR MEDIUM ON WHICH TO GROW *T. viride* ON COMMERCIAL SCALE (10 TONS/DAY)

Item	lb/day	cents/lb	\$/day
KH_2PO_4	686	10	69
$(NH_4)_2SC_4$	480	10	48
Urea	103	4.7	5
$MgSO_4 \cdot 7H_2O$	103	2.9	3
$CaCl_2$	103	29	30
$FeSO_4$ $7H_2O$	1.72	10	--
$MnSO_4$ H_2O	0.54	59	--
$ZnSO_3$ $7H_2O$	0.48	5	--
Peptone	175	20	35
NaOH (pH control)	20	28	6
Plus 25% shipping, handling, storage, etc.			
Total Raw Material Costs for 10 tons cellulose per day			246.

TABLE 72

SUMMARY OF FIXED CAPITAL COSTS FOR A TEN-TON PER DAY "BIOFRACTIONATION" PLANT

Item	\$ Cost	%
1. Cellulose Pretreatment Shredding Heating Grinding	\$ 219,000.	11.1
2. Enzyme Production Fermentation Air & Medium Sterilization Medium Supply System	1,036,000.	52.6
3. Cellulose Hydrolysis	245,000.	12.4
4. Cellulose Recycle and Product Recovery Filtration Drying	470,000.	23.9
Total	\$1,970,000.	100.0

TABLE 73

MAJOR EQUIPMENT FOR A TEN-TON PER DAY "BIOFRACTIONATION" PLANT

Item	Size/Capacity	Uninstalled Cost	Installed Cost
Fermenters (4)	52,000 gal	$240,000.	$276,000.
Hydrolysis vessel	69,400 gal	67,500.	77,600.
Filter 1	24 sq ft surface	21,000.	27,000.
Filter 2	90 sq ft surface	37,000.	48,000.
Air filter	465 SCFM	3,000.	4,000.
Shredder	1,000 lb/hr	10,000.	12,500.
Heater	1,000 lb/hr	14,600.	18,600.
Grinder	1,800 lb/hr	25,000.	31,250.
Dryer 1	150 sq ft surface	12,200.	14,700.
Dryer 2	1,270 sq ft surface	58,000.	70,000.
Heat exchanger 1	85 sq ft	3,000.	3,300.
Heat exchanger 2	50 sq ft	2,400.	2,640.
Heat exchanger 3	200 sq ft	4,500.	4,950.
Heat exchanger 4	30 sq ft	1,800.	1,980.
Air compressor	500 SCFM	10,500.	13,500.
Medium supply tanks (2)	10,000 gal	32,400.	36,900.
Fermenter motors (4)	10 hp	4,200.	8,400.
Hydrolysis unit motor	20 hp	1,500.	3,000.
Medium supply motors (2)	5 hp	1,500.	3,000.
Solids feeder	1,800 lb/hr	750.	850.
Screw conveyors (2)	1,000 lb/hr	10,400.	11,400.
Centrifugal pumps (3)	50 gal/min	2,025.	2,235.

TABLE 74

COST REDUCTIONS FROM PROCESS IMPROVEMENTS

1. Manufacturing Cost vs. Plant Size – $ per ton cellulose

	10 tons/day	100 tons/day[a]	100 tons/day[b]
Raw Materials	24	24	24
Utilities	23	23	23
Labor Based Costs	92	9	9
Fixed Capital Based Costs	104	74	41
Total	243	130	97
Interest on Investment (6%)	33	23	12
Annual Processing Cost	276	153	109
Glucose Value at $0.08/lb	146	146	146
Net Gain	-130	-7	+37

2. Process Improvements – Cost Reduction – $ per ton of cellulose

	10 tons/day	100 tons/day[a]	100 tons/day[b]
(1) Elimination of Grinding (6% of fixed capital, 18% of utilities)	12	10	7
(2) Elimination of Cellulose Recycle – (Reprocessing) (38% of utilities, 19% of fixed capital)	35	27	19
(3) Double Fermentation Rate (20% of fixed capital)	27	19	11

[a] Fermenters and hydrolysis vessels scaled-up directly, remainder of plant scaled-up according to 0.6 power rule. Fixed Capital Cost = $14,000,000.

[b] Entire plant scaled-up according to 0.6 power rule. Fixed Capital Cost = $8,000,000.

VI. INCINERATION – PYROLYSIS-COMBUSTION

INTRODUCTION

The pyrolysis of organic matter under conditions of temperature and time sufficient to convert that matter to gaseous products and the subsequent combustion of those products is a modified form of incineration that we have named pyrolysis-combustion. The important difference from conventional incineration is that the processes of gaseous fuel formation and its combustion are separated in time and space. This permits a great deal more flexibility during the process of burning an organic material even when the only objective is the disposal of a solid waste. Moreover, the process can be designed to use the organic material for the production of heat and power and for the production of chemicals of commercial value. Solids, suspensions, or solutions can be utilized as the raw material; therefore, a wide range of domestic, industrial, agricultural, commercial, and special solid wastes can be accommodated.

As described in the Second Annual Report [1] on this project, the research work which serves as a basis for the pyrolysis-combustion process was carried out using a 50% aqueous solution of the organic matter dissolved during the pulping of wood with sodium hydroxide and sodium sulfide – known in the industry as kraft black liquor. However, it was recognized that the process should be generally applicable to organic matter and specifically applicable to most forms of solid wastes. The research and initial phases of design of a demonstration unit to establish the technical and economic feasibility for using the process in the recovery cycle of the kraft pulping process had been carried out when the decision was made to direct the incineration phase of this project into high-temperature pyrolysis-combustion. The progress made during the past year is described in this report.

Rationale

The rationale for developing the concept of pyrolysis-combustion for the disposal or, more properly, utilization of solid wastes for the production of power and ultimately for the production of chemicals was presented in the Second Annual Report. In order to achieve the maximum rates of gasification of the organic raw material, the temperature used in pyrolysis should be the maximum that is practical. As previously pointed out, this is particularly important in the steam-char reaction in which carbon monoxide and hydrogen are produced. For this reason the experimental unit has been designed to be operated at temperatures up to 1200°C in the pyrolysis zone. The maximum temperature that can be used will be limited by some factor such as material from which the reactors are fabricated, the formation of a slag or smelt that is undesirable, or, possibly, the occurrence of a reaction that would form an undesirable end product. To effect the heat transfer necessary for the evaporation of water, a lower temperature pyrolysis zone was employed so that external heating of a metal wall could be used. To attain the high final temperature specified, a reactor using a high temperature, alkali-resistant ceramic has been designed and constructed. A gravity transfer system between these two units (a device for collecting ash or slag if a smelting temperature is employed and a burner for flaming the pyrolysis gases) has been provided. Since solid wastes cover a spectrum of raw materials and, indeed, as an area of study are considered to include the disposal of solvents and solutions or suspensions of organic matter as well as solids, two feed systems have been provided – one to accommodate pumpable fluids, the other for conveyable solids.

In the design of the pyrolysis-combustion process, particular attention has been given to the avoidance of producing an air pollution problem which has plagued conventional incineration processes. The process has been specifically designed with the objectives of eliminating the emission of malodorous products such as those that have characterized modern kraft pulping recovery systems, eliminating sulfur dioxide emmission, or at least reducing it to a level well within the limit that is contemplated as acceptable in the ambient air in the vicinity of the installation, and eliminating emission of particulate material. The gases produced will be used to furnish the energy required to carry out the process; excess can be converted to power. Chemical production can be an ultimate goal of the process which could be of substantial importance in process economics.

The experimental unit has been built to study the process on a continuous basis and to obtain data to establish a reliable engineered system for processing of organic solid wastes on a technically and economically feasible basis that will satisfy the key considerations pertaining to public health and environmental impact.

Objectives

The objectives of this study during the interim since the last report were the major construction and shakedown of the experimental pyrolysis-combustion unit in which the research and developmental work could be carried out to demonstrate the process. The objective in the next phase of the work is to operate the unit to demonstrate the technical feasibility of the process in the disposal of solid wastes. Data obtained can then be used to provide information for design and economic evaluation of the process. As previously stated, the long-term objectives are the conversion of organic matter to 1) usable energy, and 2) commercially valuable products, with no organic residue, and with no or minimal (i.e., below established acceptable limits) introduction of pollutants to air or water resulting from such processing.

PYROLYSIS-COMBUSTION EXPERIMENTAL UNIT

Construction of the pyrolysis-combustion experimental unit as an outdoor structure has been completed as contemplated for initial operations. Monitoring and control equipment with a visual display indicating status of operating functions have been installed on a panel which is housed in a control building. Shakedown procedures in which water has been introduced into the heated pyrolysis zones which simulate the introduction of an aqueous solution or suspension have been carried out to prove the reliability of the various pieces of equipment and to calibrate the equipment with respect to temperature, pressure, and flow parameters. Testing and calibration of the ancillary feeding, pyrolysis gas burning, air supply, and control equipment are proceeding satisfactorily and should be essentially completed in the interim period covered by this report.

Pertinent Considerations in Construction of the Experimental Unit

In laboratory investigations of the pyrolysis of solutions of organic material having a high basic ash content, as, for example, draft black liquor, it was found that temperatures on the order of 1,000°C should be maintained in order to produce simple fuels at maximum rates [30,31] with minimum concentrations of sulfur-containing organic compounds. However, at temperatures in excess of 750°C in the pyrolysis of kraft black liquor, equipment fabricated from all but the most exotic alloys (corrosion resistant) becomes prohibitively expensive. Therefore, to supply the heat required for endothermic reactions and to vaporize water present in a wet feed, indirect heating by transfer through a metal wall was indicated. Accordingly, to accommodate these divergent needs for high rates of heat transfer and for high temperature under highly corrosive conditions, it was concluded in early design considerations that at least two stages should be used in the pyrolysis process [32].

In principle, the feed is dried in the first stage and pyrolysis is carried out to the extent that a nonagglomerating, particulate solid is formed which can be continuously fed to the second reactor. Second-stage pyrolysis should be carried out in a ceramic reactor that can be operated at temperatures up to 1,200°C. Accordingly, the second reactor was fabricated from a 3,400°F, high purity, 97% tabular alumina castable ceramic. This material can withstand extreme temperature conditions, is resistant at elevated temperatures to an alkaline environment (specifically to a smelt of sodium carbonate and sodium sulfide), and because of its very low iron content, has a high resistance to carbon monoxide disintegration. To minimize heat losses in the second-stage reactor, two side walls are heated. Since combustion of pyrolysis gas would be used to provide the heat required in a full-scale application of the process, it was decided to employ gas heating for all stages in the pilot plant. In initial studies, for reasons of uniformity in experimental design, natural gas is being used. However, by relatively simple modifications, the pyrolysis gas could be used for this purpose.

The low thermal conductivity of the ceramic materials used in the fabrication of the second reactor makes it impossible to reach the required high temperatures by indirect heating. Accordingly, it is planned to meter into the second-stage reaction zone at the point of introduction of combustible gases and solids from the first-stage reaction zone, an amount of air with which sufficient heat can be generated through exothermic reactions to maintain the temperature of the zone at the desired level. Since it is desirable to use a minimum amount of air to maintain this temperature, an air preheater will be used. In addition, a minor amount of heat transfer through the heated ceramic wall will be provided by maintaining the temperature of the heated side of the wall somewhat higher than the temperature in the pyrolysis chamber. It is anticipated that the oxygen in the admitted air will be completely consumed within a restricted zone of the reactor. Conditions beyond this oxidation zone will again become reductive, and completion of the pyrolysis reactions will take place.

Experimental Unit Construction

The design of the experimental unit has been described in the Second Annual Report and in Master's dissertation by Basu [33,34]. The unit consists of an outdoor structure on a concrete pad. A two-story, metal frame was erected on the pad to support the first-stage pyrolysis unit and auxiliary equipment. The accompanying photograph (Figure 17) shows the unit completed as of April 1970.

The major equipment items are the first- and second-stage pyrolysis reactors. These may be considered as fixed pieces of equipment around which the auxiliary equipment items can be arranged in various configurations to develop process designs most suitable to the attainment of the objectives of this research.

In initial studies, it is planned to use an equipment configuration in which the feed can be either a solution pumped from a tank or a solid conveyed from a solid wastes hopper. The hopper is provided with an agitator to prevent bridging of material. Solid feed will enter the bottom of the reactor just above the point at which pyrolysis gas is recycled. A schematic of the pyrolysis-combustion unit in the configuration to be used initially in studying solid wastes is shown in Figure 18.

First Stage. The first-stage pyrolysis reactor (Figure 19), a cylindrical vessel 8 in. in diameter and 6 ft in length, was fabricated from stainless steel (type PH 15-7 MO) having high corrosion resistance to a reducing type environment and a higher transition temperature than other types (316 or 321). The top and bottom of this reaction vessel are flanged and may be removed to accommodate various feed and product removal configurations. Five thermocouples were welded at equally-spaced intervals from top to bottom of the reactor wall to measure reactor wall temperatures. The vessel is suspended in a gas-fired furnace built of two layers of insulation brick and encased in a steel shell. An annular heating space was provided with two gas burners at the base to impart efficient cyclonic movement of the combustion gases. Thermocouples were placed in the annular space as sensors for the temperature indicator – controllers which regulate the flow of gas to the two burners. A stack is provided to discharge the combustion gases at a safe distance above the top of the unit.

In the present configuration, pyrolysis gases and entrained solids are removed from the top of the reactor and passed through a cyclone separator. The gas effluent from the top of the cyclone is fed to a hot-gas blower having specifications

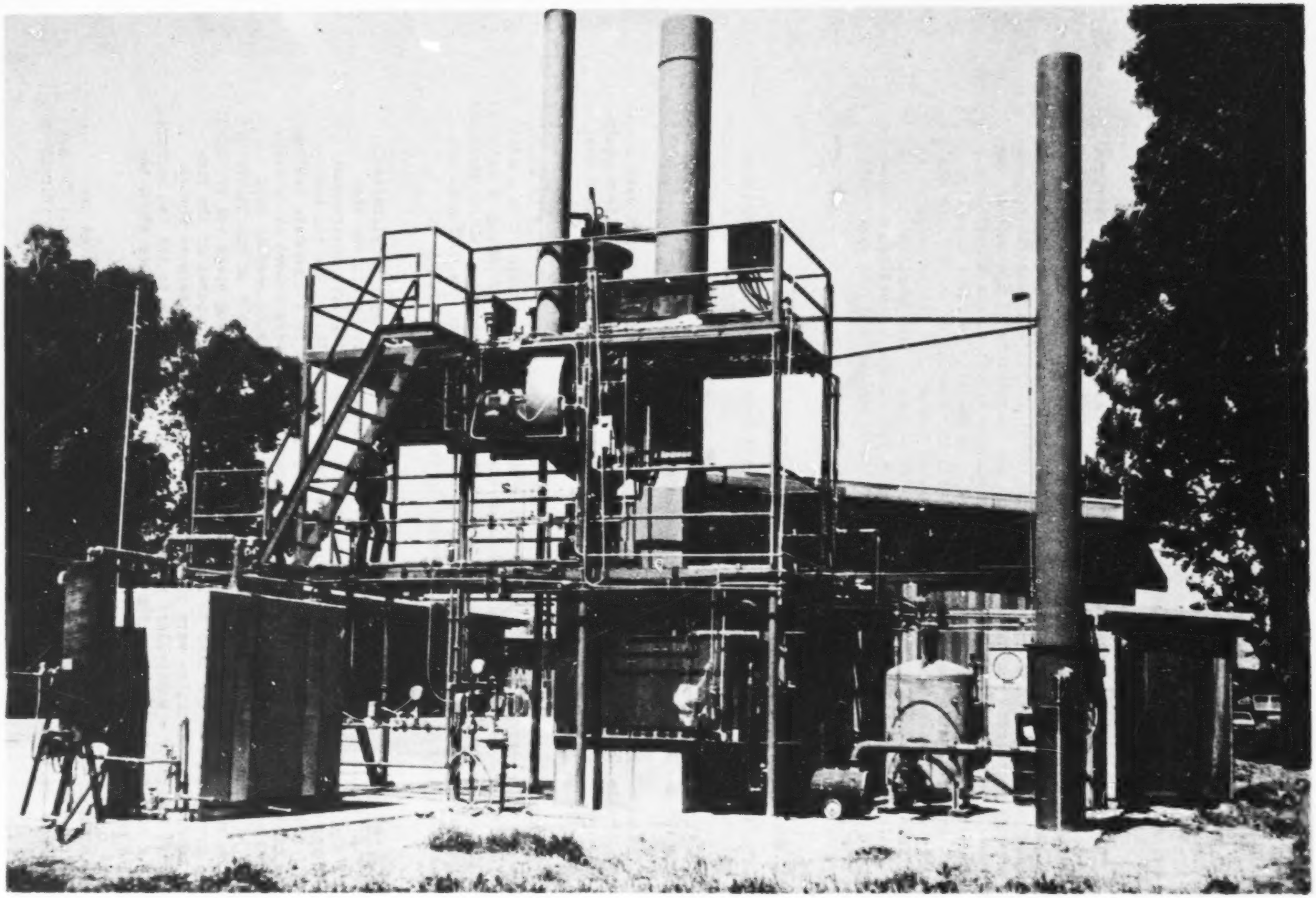

FIGURE 17. PYROLYSIS-COMBUSTION UNIT

SW 115

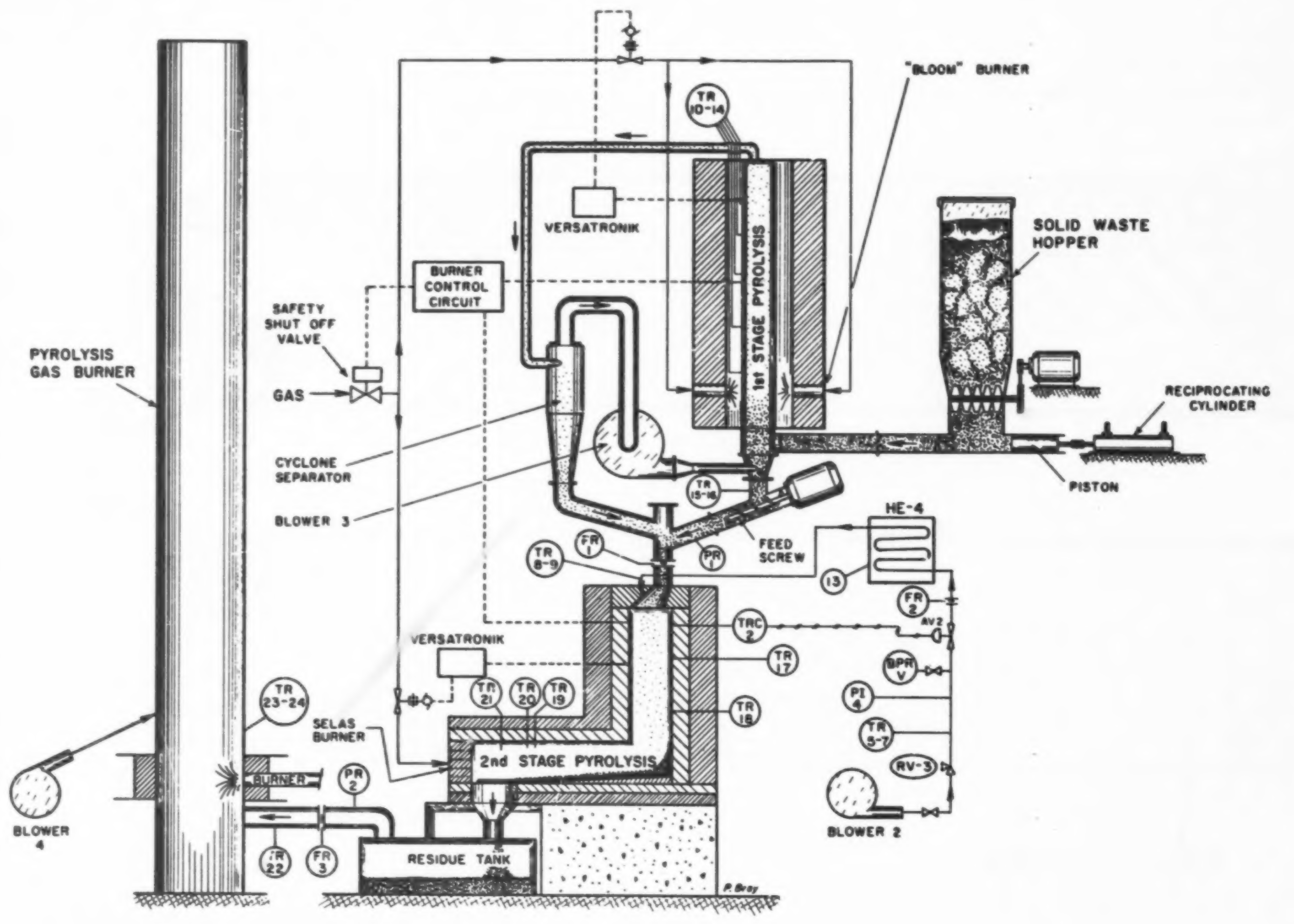
"BLOOM" BURNER
TR 10-14
VERSATRONIK
1st STAGE PYROLYSIS
SOLID WASTE HOPPER
BURNER CONTROL CIRCUIT
SAFETY SHUT OFF VALVE
PYROLYSIS GAS BURNER
GAS
RECIPROCATING CYLINDER
CYCLONE SEPARATOR
TR 15-16
PISTON
BLOWER 3
HE-4
FR 1
FEED SCREW
TR 8-9
PR 1
13
FR 2
TRC 2
AV2
VERSATRONIK
TR 17
BPR V
TR 23-24
TR 21
TR 20
TR 19
PI 4
TR 18
SELAS BURNER
TR 5-7
2nd STAGE PYROLYSIS
RV-3
BURNER
PR 2
BLOWER 4
BLOWER 2
TR 22
FR 3
RESIDUE TANK
P. Bray

FIGURE 18. CONFIGURATION OF PYROLYSIS-COMBUSTION UNIT WHEN PROCESSING SOLID WASTES

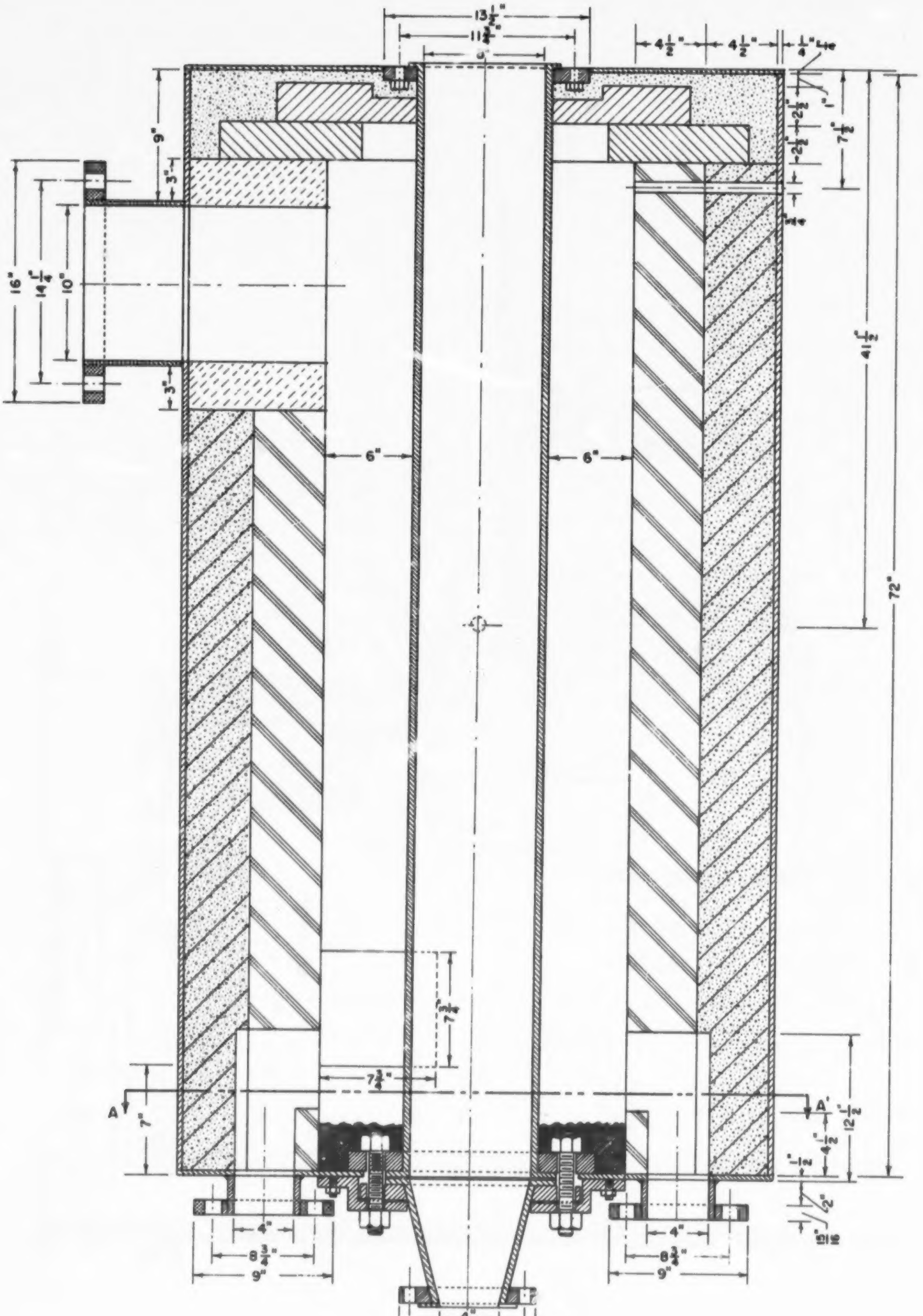
13½"
11¾"
9"
4½"
4½"
¼" Lie
2½"
2½"
7½"
1"
¼"
9"
3"
3"
16"
14¼"
10"
41½"
72"
6"
6"
7¼"
7¾"
A
A'
7"
12½"
4½"
½"
½"
15/16"
4"
8¾"
9"
4"
8¾"
9"
4"
8¾"
9"

FIGURE 19. FIRST-STAGE PYROLYSIS REACTOR

for handling gases up to 1300°F. The blower will discharge gas into the cone-shaped bottom of the reactor through a tangential entry. If solids build up in the reactor and are not carried out in the top discharge, they can be conveyed out of the bottom of the cone by way of a 4 in.-diameter pipe to a screw conveyor. The screw conveyor discharges to a vertical pipe which is common with the discharge from the cyclone separator.

Second Stage. The gas stream containing the partially pyrolyzed solids is charged to the top of the second-stage reactor (Figure 20). This reactor was designed to have a 6 ft vertical section joining a 6 ft horizontal section. The vertical section is 9 in. wide and 12 in. deep, whereas the horizontal section is 9 in. wide and 18 in. deep at the discharge end of the reactor. The floor of the horizontal section slopes approximately 1 in. per foot and in cross-section from either side to the center. The discharge port in the floor of the furnace is a cast ceramic plug with a 3 in.-bore. The side walls of the reactor are common to combustion chambers on either side of the pyrolysis chamber. The pyrolysis chamber was cast entirely of specially selected alumina castable ceramic. The other three walls of the combustion chambers were constructed of a basic-chrome ceramic brick. The top of the chambers and the floors of the combustion chambers were cast, using the castable ceramic. Two layers of fire brick, a layer of insulating board, and lastly a steel housing completely enclose these three chambers. The reactor was built on a layer of fire tile which is supported on a steel plate fastened to a combination concrete pier and steel stand. An "ash collector" is provided to receive gases and solids or slag (smelt) discharged from the port in the pyrolysis zone.

Gas burners fire into the front end of each combustion chamber immediately adjacent to the discharge end of the pyrolysis chamber. The temperature of the combustion chambers is controlled by the use of instrumentation identical to that used for the first-stage pyrolysis reactor. An interlocking system for supplying gas to the burners, controlling temperature, and sensing the pilot flame of each burner has been provided.

Gases are discharged through the ash collector to a device for their combustion. A tank through which water can be recirculated and sprayed has been provided for cooling the gas in order to study simple scrubbing operations.

Appropriate sensing of temperatures, pressures, and gas flows is provided so that accurate measurement of conditions in the unit can be made. The instruments for these controls, for control of gas and air to the gas burners, and switches for energizing the blowers, pumps, and other electrical devices are assembled on a control panel housed in an 8 ft x 12 ft building immediately adjacent to the unit. Cabinets have been supplied to house air blowers and the liquid feed system.

RESEARCH PROGRAM

The plan for the study of pyrolysis-combustion involves the sequential investigations of various types of solid wastes. Thus, information gained in the investigation of one type can be applied to and should facilitate the investigation of each subsequent type selected for study.

Since the ligno-carbohydrate type of material is the most abundant of all the wastes in the solid wastes stream, the logical course of action is to select a typical material from this category of wastes. Secondly, the type of material selected for the initial studies should pose no problems with respect to feeding it into the reactor, since the development of a feeding device suitable for use with all types of wastes is one of the continuing objectives of the research program. Particulate wood is a material which meets both of these criteria and it was selected for use in the initial studies. When satisfactory operation of the experimental unit is achieved using wood the study of comminuted solid wastes supplied from a commercial operation will be undertaken.

Introduction of materials into the pyrolysis unit is considered a research area to be investigated and will be given special attention. Size, shape, and condition of particles will be an important aspect with regard to feeding and to pyrolysis characteristics.

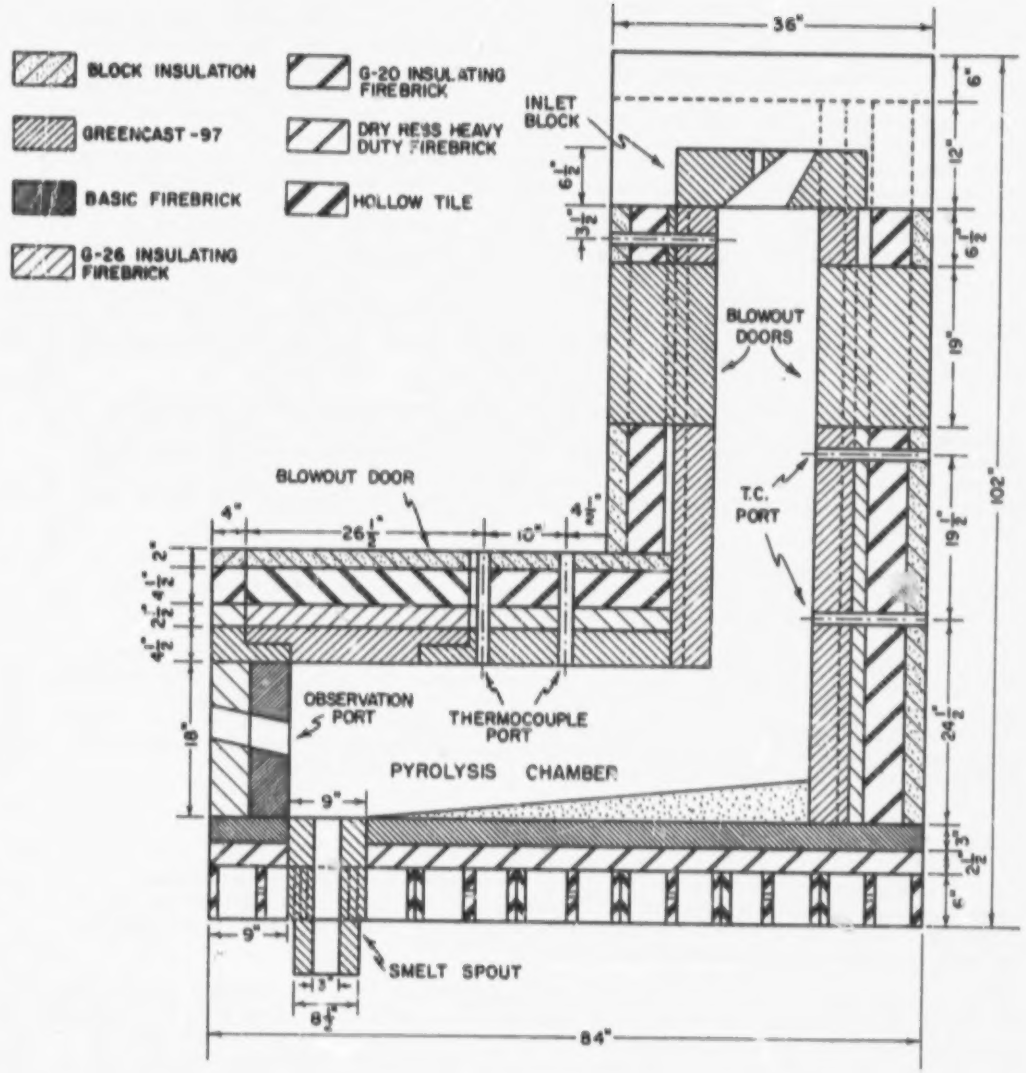
BLOCK INSULATION
GREENCAST-97
BASIC FIREBRICK
G-26 INSULATING FIREBRICK
G-20 INSULATING FIREBRICK
DRY PRESS HEAVY DUTY FIREBRICK
HOLLOW TILE
INLET BLOCK
36"
6"
12"
6 1/2"
3 1/2"
6 1/2"
19"
BLOWOUT DOORS
T.C. PORT
19 1/2"
102"
24 1/2"
BLOWOUT DOOR
4"
26 1/2"
10"
4 1/2"
2"
4 1/2"
2 1/2"
4 1/2"
18"
OBSERVATION PORT
THERMOCOUPLE PORT
PYROLYSIS CHAMBER
9"
3"
2 1/2"
6"
9"
SMELT SPOUT
3"
8 1/2"
84"

FIGURE 20. SECOND-STAGE PYROLYSIS REACTOR

The method of introduction of the raw material into the first pyrolysis zone in initial studies will be in the nature of a bottom-feed type with material pneumatically conveyed in the reactor. A simple change in this configuration can be made by the addition of a stand-pipe of appropriate diameter and length, centrally located in the reactor, and connected to the bottom outlet. Then, as solids are introduced and pyrolysis is effected, the partially pyrolyzed solids moving to the top of the fluidized bed would overflow into the stand-pipe and be delivered to the screw conveyor. Gas would be removed from the top of the reactor to supply the hot-gas blower. That portion of the gas stream not recirculated by the blower, as well as the separated solids, will be discharged from the cyclone and delivered with the solids from the screw conveyor to the second pyrolysis stage. A top-feed configuration could be provided by placing a baffle in the center of the reactor extending a distance from the top. One side of the reactor would then serve for introduction of solids by free fall. The bottom and other side of the reactor could be operated to provide a moving-bed type pyrolysis with removal of gas taking place from the reactor top and solids conveyed from the bottom.

When solutions or light suspensions of solids are pumped into the reactor, a top-feed, free-fall type of operation can be studied. Furthermore, solutions or suspensions can be introduced at the bottom or at an intermediate point in the reactor, thus providing a fluidized, bed-type of pyrolysis. Specialized equipment for handling slurries would have to be provided.

Ram feeding was considered as a technique which might be most generally applicable and thus was incorporated in the original design. This feeding mechanism can be adapted to a screw feed or a belt feed simply by replacing the piston with an appropriate device. It also is possible that a gravity feed with entry through a rotary feed located away from the high temperature zone of the reactor could be devised.

Clearly, a number of configurations of this equipment are possible. As experience is gained with the configuration initially used, needed changes will be more clearly defined. At appropriate times these changes can be made with relatively minor rearrangements or additions to the basic equipment.

The parameters to be studied in the operation of the experimental unit include:

1. The physical condition (particle size, moisture content) of the feed.
2. The rate of feeding (lb/hr) which will be a factor in establishing residence times in the two pyrolysis stages.
3. The mode of feeding.
4. The wall temperature of reactor 1 (initially 500°C).
5. The gas temperature in reactor 2 (initially 1000°C).
6. The rate of gas recycle.
7. The temperature of gas recycle.

In planning the experimental program, each of these variables will be investigated systematically.

Data will be obtained on composition of the pyrolysis products, on heat requirements, and on the rates of pyrolysis. Based upon the results, process designs will be optimized and the most favorable operating conditions will be determined. The optimized results will be verified.

The experimental results can be used in developing the design of pilot- or large-scale operations, and in making an economic analysis of the proposed process.

A specific part of the experimental program will involve the separation of organic pyrolysis products on a scale large enough to permit a thorough investigation of their chemical composition, of yield of major products of commercial significance, and of processes that can be used for their purification. Such a separation might be effected following either the first- or second-stage pyrolysis.

ANALYTICAL METHODS

Appropriate sampling of the pyrolysis products will be made at several stations provided in the experimental unit. In obtaining these samples the gases will be cooled and condensable products will be collected. The uncondensed gases will be analyzed by the gas-solid chromatographic technique perfected in the laboratory studies [31] in order to obtain the concentrations of components including: hydrogen, carbon dioxide, carbon monoxide, nitrogen, oxygen, methane, ethane, ethylene, propane, and propylene. The condensed aqueous phase and any organic phase which is separated will be analyzed by the system employing gas-liquid chromatography previously described [32,35,36]. If sulfur compounds are present in either uncondensed gas or condensed liquid phases these can be quantitatively analyzed for sulfur using this system which involves dual detection of the stream eluting from the chromatograph by flame ionization and by microcoulometric titration. This system using the latter detector can also be used for the quantitative determination of chlorine in volatile compounds.

Instrumental methods of analysis available to compliment gas chromatographic analyses include infra-red, mass spectography, and nuclear magnetic resonance spectrometry. The chromatographic system used for preparing samples for IR and MS analyses and various organic compounds identified in the pyrolysis products have been described [35].

LABORATORY-SCALE PYROLYSIS OF SOLID WASTES

The laboratory apparatus employed in the pyrolysis of kraft black liquor [31] has been modified to introduce a solid feed. In order to simulate the continuous pyrolysis of solid wastes with an appreciable moisture content, water can also be introduced at a continuous rate. This equipment can be heated to a temperature up to 1200°C and thus can be used to study the "steady state" pyrolysis characteristics of any given solid waste material that will be studied in the continuous pyrolysis-combustion experimental unit. Preliminary results using wood appear to be similar to those obtained using kraft black liquor. Because of the turbulence occurring under the conditions used in this work, however, particulate carbon was not retained in the reactor (pyrolysis temperature was 1000°C and the water feed rate, 3 mℓ/min). Accordingly, complete gasification of the wood was not studied in the preliminary work, and conditions of pyrolysis will be altered to achieve this end. Even so, approximately two liters of gas per gram of wood introduced was produced.

VII. WET OXIDATION OF ORGANIC SOLID WASTE MATERIALS

INTRODUCTION

Wet oxidation has been applied to organic wastes to meet a variety of industrial disposal objectives. Under severe oxidative conditions these wastes have been degraded to inert gases and water and only thermal and mechanical energy and inorganic chemicals have been recovered; under less severe conditions these materials have been converted to a more convenient form for physical disposal or utilization as fuel. The recovery of organic chemicals for their chemical value under these conditions has largely been neglected, and the question of their potential production from such waste materials left unanswered.

Objectives

The objectives of this phase of the overall research was the reduction of the solid wastes stream under conditions of wet oxidation and the coincident recycling of such wastes back to basic resources such as thermal energy and organic chemicals of commercial utility.

Rationale

The overall promise of wet oxidation as currently being utilized for the disposal of waste materials and the potential of this reaction for the production of organic chemicals, as indicated by studies at this and other laboratories, provides the justification for this approach. Furthermore, the utilization of solid wastes for the production of organic chemicals under these conditions involves a unique application of wet oxidation.

RESEARCH PROGRAM

The research program was divided into three experimental phases concerned with 1) basic reaction relationships, 2) oxidation of organic solid wastes, and 3) process design.

Phase I – Determination of Basic Reaction Relationships

The initial stage of this phase was devoted to modification and to design and fabrication of equipment needed to accommodate a batch type, laboratory-scale wet oxidation process. The process is diagrammed in Figure 21. Reactions were carried out with hammermilled, air-dried white fir wood to establish basic reaction relationships and to relate their results to those of earlier studies. Reaction parameters under consideration included time, temperature, total and partial pressures, solids concentration, and agitation. Oxygen consumption and carbon dioxide – carbon monoxide formation were followed by gas-solid chromatography and pressure-volume relationships. Components of the reaction mixture were separated by vacuum filtration and subjected to physical and chemical analyses to establish material and energy balances. Dissolved organic chemical yields were determined by gas-solid and gas-liquid chromatography. Computerized data reduction systems were developed for the determination of material and energy balances, reaction gas consumption and formation, and dissolved organic chemical yields.

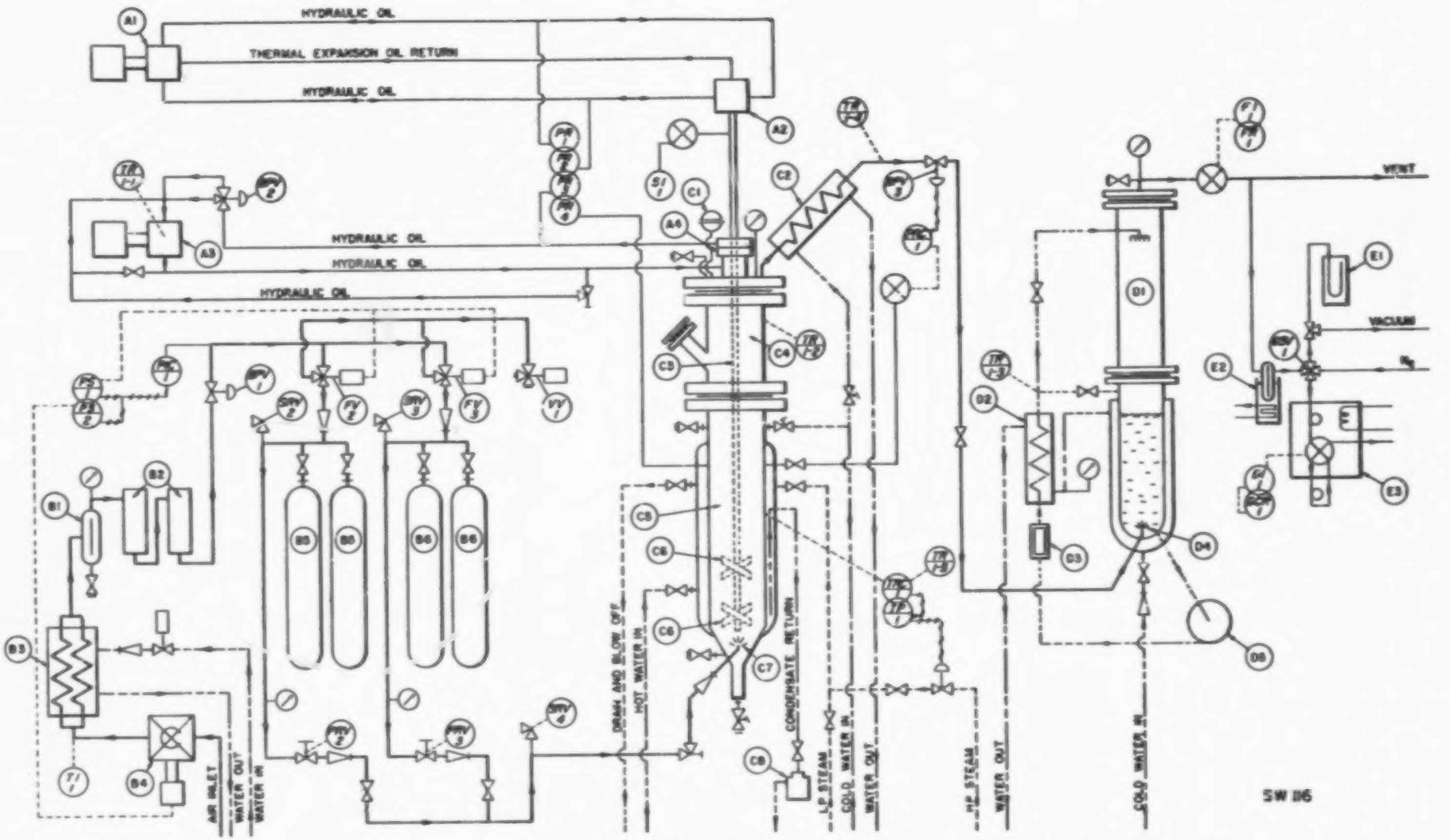
A1
A2
A3
A4
HYDRAULIC OIL
THERMAL EXPANSION OIL RETURN
HYDRAULIC OIL
HYDRAULIC OIL
HYDRAULIC OIL
HYDRAULIC OIL
B1
B2
B3
B4
B5
B5
B6
B6
C1
C2
C3
C4
C5
C6
C6
C7
C8
D1
D2
D3
D4
D5
E1
E2
E3
VENT
VACUUM
N_2
AIR INLET
WATER OUT
WATER IN
DRAIN AND BLOW OFF
HOT WATER IN
CONDENSATE RETURN
L P STEAM
COLD WATER IN
WATER OUT
H P STEAM
WATER OUT
COLD WATER IN
SW 116

FIGURE 21. SCHEMATIC DIAGRAM OF BATCH WET-OXIDATION PROCESS

LIST OF SCHEMATIC EQUIPMENT SYMBOLS FOR FIGURE 21

Symbol	Description
A-1	Agitator hydraulic pump
A-2	Agitator hydraulic motor
A-3	Mechanical seal hydraulic pump
A-4	Mechanical seal
C-1	Rupture disc
C-2	Off-gas cooler
C-3	Agitator shaft
C-4	Reactor extension
C-5	Jacketed reactor
C-6	Turbine blade
C-7	Sparger
C-8	Impulse steam trap

Symbol	Description
B-1	Moisture-oil separator
B-2	Chemical drier
B-3	Aftercooler
B-4	Air compressor
B-5	Air cylinders (Bank 2)
B-6	Air cylinders (Bank 3)
D-1	Off-gas scrub tower
D-2	Heat exchanger
D-3	Rotometer
D-4	Sparger
D-5	Circulation pump
E-1	Manometer
E-2	Refrigerated moisture trap
E-3	Gas chromatograph

Phase II – Oxidation of Organic Solid Waste Materials

In this phase the experimental techniques and results of phase I were to be applied to additional organic waste materials such as municipal garbage, agricultural residues, sewage sludge, industrial effluents, and combinations of these and other wastes. Reaction conditions would be optimized for the production of a particular organic chemical or group of chemicals; and, in the latter stage of this phase, continuous operation would be simulated by periodic introduction of additional material.

Phase III – Process Design

In this phase the results of the preceding phases would be used in developing possible process designs for the production, isolation, and utilization of organic chemicals and for the utilization of thermal and mechanical energy from wet oxidation of solid waste materials.

EXPERIMENTAL WORK

During the period covered by this report, the research team was primarily involved with the completion of the analytical and data reduction aspects of phase I of the research program and with the modification of the overall reaction system in preparation for the investigative stage of phase II.

Reaction mixtures from phase I were subjected to extensive chemical and physical analyses. Preliminary material balance and gas consumption-formation data given in the Second Annual Report were completely revised. The revised data are shown in Tables 75 and 76. Energy balances for these reactions, presented in Table 77, were established by calorimetric analyses of the residual solids and nonvolatile dissolved solids and by gas chromatographic analyses of the volatile dissolved solids and off-gases. Dissolved organic chemical yields, described in Table 78, were determined by gas-solid chromatography of the volatile dissolved solids and by gas-liquid chromatography of the nonvolatile dissolved solids following freeze drying and silylation. In addition, four FORTRAN IV computer programs were written for the reduction of raw reaction and analytical data to the above material and energy balance, gas consumption-formation, and organic chemical yield information.

Upon completion of the phase I analytical activities some modifications of the reaction system were made. These included: a) installation of a Honeywell pneumatic stem positioner on the back-pressure control valve to allow automatic control of total reaction pressure; b) installation of a third bank of air cylinders to enlarge compressed air storage; c) installation of a Foxboro 3-pen pressure recorder on the air storage system to provide continuous monitoring of air consumption; d) addition of a third turbine blade to the agitator to promote greater mixing action; and, e) installation of single stage regulator to provide constant input air pressure to the reactor.

As indicated previously, intermediate levels of degradation of waste materials is a primary concern in this study because they control both the quality and quantity of potential organic chemical production. Results from phase I reactions indicate that maximum dissolved solids yield, 36% of total carbon input, occurred at 200°C and 2 cu ft/min air input. Residual solids yields decreased and volatilized carbon yields increased with temperature increase; dissolved solids yields increased with temperature to maxima at 180° to 200°C and then decreased.

Mechanistically these results suggest that there are two major steps in the degradation reaction, namely hydrolysis and oxidation, and that oxidation is the rate limiting step. At 160°C, hydrolysis prevails as indicated by the low volatilized carbon yields and oxygen consumption; at 220°C oxidation has substantially increased as shown by the higher volatilized carbon yields and oxygen consumption and by the lower dissolved solids yields.

Individual organic chemical yields, primarily hydrolytic or oxidative degradation products of the component pentose and hexose polymers of wood, show varying trends. Yields of aldose monomers, such as glucose, mannose, and xylose, are high at 160° to 180°C but drop off sharply with further increase in temperature. At 220°C yields of the low carbon number aliphatic acids, such as acetic and formic, are dominant. These results coupled with the residual solids and dissolved solids yields indicates that the oxidation step involves the dissolved solids rather than the residual.

In short, organic chemical production under the conditions of phase I reactions occurred at moderate temperatures, namely, 180° to 200°C. Higher temperatures would undoubtedly increase total solids reduction and, in addition, cause conversion of an increasingly larger amount of dissolved organic solids to acetic acid and inert gases.

TABLE 75

MATERIAL BALANCE FOR WET OXIDATION REACTIONS OF WHITE FIR WOOD

Reaction Number	Reaction Conditions[a]				Reaction Influent		Reaction Effluent				
							Residual Solids		Dissolved Solids		Volatilized Solids
	Temp °C	P_{tot} psig	P_{air} psia	Air Flow cfm	Total Solids g	Total Carbon g	Total Solids g	Total Carbon g	Total Solids[b] g	Total Carbon[c] g	Total Carbon[d] g
WO-1-6	160	225	150	2	4,000	1,970	2,468	1,263	935	465	72
WO-1-7	160	225	150	1	4,000	1,970	2,744	1,380	940	459	60
WO-1-4	180	280	150	2	4,001	1,970	2,242	1,176	1,541	512	314
WO-1-5	180	280	150	1	4,000	1,970	2,448	1,282	1,436	549	211
WO-1-1	200	395	180	1	4,000	1,970	1,906	1,084	1,315	298	355
WO-1-2	200	360	150	2	4,005	1,972	1,440	811	1,422	570	568
WO-1-3	200	360	150	1	4,001	1,970	2,109	1,172	1,169	471	387
WO-1-8	220	470	150	1	4,000	1,970	1,944	1,184	760	365	438
WO-1-9	220	470	150	2	4,000	1,970	1,480	884	736	285	676
WO-1-10	220	470	150	1	4,000	1,970	2,090	1,244	640	334	364

[a] All reactions were carried out in 40 liters of water, for 2 hours at temperature, and with 600 rpm agitation.

[b] Calculated from gas chromatographic analyses.

[c] Calculated from total carbon analyses.

[d] Calculated from weight of carbon dioxide-carbon monoxide.

TABLE 76

REVISED OXYGEN CONSUMPTION AND CARBON DIOXIDE - CARBON MONOXIDE FORMATION IN WET OXIDATION REACTIONS OF WHITE FIR WOOD[a]

Reaction Number	Gas Consumption				Gas Formation					
	O_2add. g	O_2cons. g	O_2cons./O_2add. %	O_2cons./100g Sol. Carbon g	CO_2 g	CO_2/O_2cons. g/100g	CO_2/100g Sol. Carbon g	CO g	CO/O_2 cons. g/100g	CO/100g Sol. Carbon g
WO-1-6	1,949	225	11.5	14.7	265	17.3	1.2	0	0	0
WO-1-7	1,064	193	18.1	15.4	214	17.0	1.1	3.5	0.3	0.0
WO-1-4	2,226	953	42.7	54.2	1,067	60.7	112.0	53	3.0	5.6
WO-1-5	1,042	688	65.9	44.3	720	46.4	104.7	34	2.2	4.9
WO-1-1	1,426	1,244	87.2	59.4	1,229	58.7	98.8	46	2.2	3.7
WO-1-2	2,326	1,688	72.6	65.9	1,948	76.1	115.4	86	3.4	5.1
WO-1-3	1,435	1,240	86.3	65.6	1,345	71.1	108.5	48	2.5	3.9
WO-1-8	1,454	1,241	85.4	60.4	1,507	73.3	121.4	64	3.1	5.2
WO-1-9	2,246	1,860	82.8	73.8	2,334	92.6	125.5	91	3.6	4.9
WO-1-10	1,219	1,059	86.8	55.4	1,256	65.8	118.6	51	2.7	4.8

[a] Gas consumption and formation calculated on the time interval starting at 155°C coming to reaction temperature and ending at 155°C coming off temperature.

TABLE 77

FNERGY BALANCE FOR WET OXIDATION REACTIONS OF WHITE FIR WOOD

Reaction Number	Reaction Influent Solids		Reaction Effluent						
			Residual Solids		Dissolved Solids		Carbon Monoxide		
	Heating value[a] k-cal/100g	Total Initial Heat k-cal	Heating value[a] k-cal/100g	Total Residual Heat k-cal	Heating value[b] k-cal/100g	Total Residual Heat k-cal	Heating value[c] k-cal/100g	Total Residual Heat k-cal	Net Heat Loss k-cal
WO-1-6	473	18,910	468	12,614	319	2,986	0	0	3,310
WO-1-7	473	18,910	458	13,158	329	3,088	445	13	2,651
WO-1-4	473	18,914	474	10,625	286	4,410	445	236	3,643
WO-1-5	473	18,910	493	12,075	297	4,270	445	151	2,414
WO-1-1	473	18,912	496	9,447	311	4,093	445	205	5,167
WO-1-2	473	18,935	480	6,919	300	4,267	445	383	7,366
WO-1-3	473	18,935	487	10,263	302	3,534	445	214	4,924
WO-1-8	473	18,910	489	9,505	312	2,372	445	285	6,748
WO-1-9	473	18,910	462	6,843	295	2,174	445	405	9,488
WO-1-10	473	18,910	515	10,763	312	2,000	445	227	5,920

[a] Calculated from calorimetric analyses.

[b] Calculated from calorimetric and gas chromatographic analyses.

[c] Calculated from gas chromatographic analyses.

TABLE 78

ORGANIC CHEMICAL YIELDS IN WET OXIDATION REACTIONS OF WHITE FIR WOOD[a]

Compound	Yield/4000 g of Wood									
	WO-1-6 g	WO-1-7 g	WO-1-4 g	WO-1-5 g	WO-1-1 g	WO-1-2 g	WO-1-3 g	WO-1-8 g	WO-1-9 g	WO-1-10 g
Acetic Acid	102	89	119	135	113	131	112	128	157	131
Arabinose	24	26	6	12	2	2	tr	tr	-	-
Benzoic Acid	52	68	92	100	94	65	63	tr	tr	tr
Formaldehyde	tr	tr	-	-	tr	-	-	tr	-	-
Formic Acid	163	120	368	263	247	338	289	148	209	137
Fumaric Acid	tr	tr	tr	7	16	5	tr	2	9	14
Furfural	-	tr	tr	tr	tr	tr	tr	tr	tr	tr
Galactose	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
Glycolic Acid	31	45	184	104	129	142	130	121	88	95
Glucose	126	115	121	145	108	117	90	17	2	9
Lactic Acid	tr	tr	13	5	5	tr	5	16	4	10
Levulinic Acid	tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
Maltic Acid	tr	3	tr	tr	6	tr	2	3	tr	3
Mannose	125	119	49	91	19	21	20	13	6	9
Methanol	28	27	33	40	51	42	51	49	46	53
Oxalic Acid	tr	21	84	45	36	25	24	tr	16	18
Succinic Acid	16	17	48	40	36	55	31	35	58	29
Xylose	68	81	49	54	41	47	41	9	8	5
Unidentified	218	209	375	395	412	432	311	219	133	127

[a] Calculated from gas chromatographic analyses of dissolved organic solids.

VIII. SUMMARY

INTRODUCTION

Progress is reported for the latter months of the third year and all of the fourth year of the research project entitled "Comprehensive Studies of Solid Wastes Management" being conducted as a multidisciplinary study of the planning, economics, operations research, public health, and technological aspects of the solid wastes problem.

In the introduction it was pointed out that the need for studies such as herein reported is the natural outgrowth of a traditional American unconcern for the conservation of resources and an unconscious indifference to "the environment." During the period covered by the report herein presented, several changes occurred relative to the need for study. On the national scene, citizens tended to group solid wastes with air and water problems into a single category of insult which defiles the total environment. Because of the concern for the total environment, the tendency was to ascribe to solid wastes a higher degree of importance than it merited as far as damage to the "ecosystem" is concerned.

The distinction was brought out between the two concepts effect of man on the environment and the effects of the environment on man. In one respect the distinction is obvious from the titles. The practical implications of the two differ. While the public has become more concerned over the effect of man on the environment, most public agencies have been more practical and have given first priority to the effect of the environment on man.

Based on the analysis and rationale given in the section Need For Study the authors of the report herein presented came to the conclusion that the need for action resulting from the failure to give the problem of solid wastes management the attention it warranted until it reached crisis proportions makes more urgent the need for study of jurisdictional, planning, economic, and systems management as a plan for action, and generates a need for technological research aimed at recycling rather than destroying resource residue.

PLANNING AND ECONOMIES

During the period since the writing of the Second Annual Report, activities concerned with the planning and economic aspects of the overall research were concentrated on refining and expanding the scope of work already underway and of that remaining to be accomplished. These activities are clarified in the present report by including in it a reformulation of detailed objectives and specific aims, and a description of the substantive progress made to date in this phase of the research. Plans also are discussed for developing a final set of objectives as well as means of implementing them.

After carefully examining the original plans of the research (cf. First and Second Annual Reports), the following ten objectives were defined:

1. Development of structural models for studying waste generation and its relationship to waste generators.
2. Empirical estimation of waste quantities and development of functional boundaries for regional analysis.
3. Development of waste multipliers in terms of quantity and composition by detailed economic activity.

4. Survey of engineering methods of disposal to acquire information for use in making economic analyses.

5. Analysis of private and public expenditure in the solid waste industry with reference to a metropolitan area.

6. Application of a mathematical model for arriving at short-run solutions based on disposal by sanitary landfill.

7. Regional economic forecasts and projections of solid wastes generation through the use of input-output studies.

8. Consideration of technical changes and new methods of transfer and disposal in terms of the management of solid wastes in the future.

9. Definition of a systems analysis approach to solid wastes management.

10. Implementation of an optimum solution, recognizing efficiency and equity criteria with reference to metropolitan or regional planning for urban services.

In conducting the survey of current and proposed engineering methods (objective No. 4 in the preceding list), available systems of solid wastes disposal were divided into "current" and "proposed" or "experimental." A brief review was made of the engineering aspects as a preliminary step leading to cost comparisons between the systems. As a part of this phase of the work, a detailed method for analyzing costs of landfill was developed, which was based on the multiple regression technique. Brief accounts were given of the experimental systems, compaction, wet oxidation, anaerobic digestion, and biological fractionation. The purpose of the comparisons and analyses was to obtain the information needed in arriving at alternative feasible bases for selecting an optimum solution.

Substantial progress has been made in fulfilling the objective "analysis of private and public expenditures in a metropolitan region by the solid waste industry" (item 5 in the list of objectives). As a part of this objective, a procedure was established for estimating waste generation in a given study region through use of waste multipliers and waste sources (cf. Second Annual Report). However, awaiting detailed examination were questions on the composition of wastes, private and public expenditures on various functions of waste management, and the implications of proposed solutions for future management of wastes. With a view to recognizing and stipulating all of these planning and economic considerations, a workable study region, namely, the Oakland metropolitan area, was defined on a functional basis for the delineation of various issues and possible methods of analysis. The Oakland metropolitan area includes seven cities and nearby urban areas, and has a population of about 800,000 people. As reported herein, the Oakland area study was started by establishing a need for public concern, defining a functional boundary for cost analysis d a need for cost data to emphasize private and public operations and the economies of scale as well as other purely economic considerations. The empirical problems encountered in collecting data and setting up an accounting framework are recounted.

The application of the mathematical model for obtaining short-run solutions based on a sanitary landfill reflects an application of the network flow model (cf. Second Annual Report) developed to solve a part of the waste management problem. Specifically, the nine-county San Francisco Bay area was chosen for the application of the model. The Bay area has about 116 points of waste generation and 74 existing and potential disposal sites. The model uses the branch-and-bound technique for optimization. As conceived and applied in the present study, the model can be used in choosing the locations of a specified number of sites to be made operational when one or more of the existing sites is filled to capacity. The problem of rerouting the waste generating points to other sites is solved by the application of the network flow model. The application as described herein should be regarded as illustrative of the uses and limitations of such mathematical models. The results should not be used at this stage for establishing policies. Further refinement of the model by way of relaxing the basic assumptions already is under way.

To recapitulate briefly, the rationale of the planning and economics phase of the comprehensive research is that some fraction of the solid wastes residue must be returned to the earth. This led to the recognition of landfill as constituting the single most important method of disposal, at least for the coming few years. Recognizing landfill as the important disposal method has implications on land-use planning. Thus there is an urgent need to conduct feed-back studies between secular land-use studies traditionally carried out by private and public planning bodies and waste management studies of the type which constitute the subject of this report. Moreover, refuse disposal already has been recognized as one of the major items for regional or Metropolitan planning along with other urban services such as air pollution, regional parks, land transportation, and regional planning in general. This aspect has serious implications from the administrative, regulative, and managerial points of view, which in waste management programs may in some instances be horizontally aggregated with other similar urban services, chiefly to reduce unnecessary multiplicity and/or conflicts in governing bodies.

OPERATIONS RESEARCH

The work done by the Operations Research Group consisted of several aspects including the following: 1) development of a mathematical program to assist the Planning and Economics Group in network flow analysis of the routing of solid wastes in the nine-county San Francisco Bay area; 2) development of a model for forecasting solid waste loadings through the use of input-output technique for the nine-county San Francisco Bay area; and 3) development of optimal strategies in capacity expansion of disposal facilities under finite and infinite planning horizons. The first of the above three, viz. the development of a network flow model was fully discussed in the section on Planning and Economics. The remaining two are briefly treated in the summary which follows:

The input-output model developed for the nine-county San Francisco Bay area consisted of 28 sectors. The output forecasts were estimated for 1966, 1970, 1974, and 1978 by these 28 sectors. Utilizing the corresponding waste loadings by individual sectors (estimated in the planning and economics studies), waste loading forecasts were developed for the four time periods. Although the original intention was to augment the usual input-output model to include additional sectors corresponding to waste industries, the augmentation of the industrial sectors was not complete at this stage of the overall research; and consequently, the results of the model are a first approximation. Similarly, the forecasts of the exogenous sectors were made for convenience and illustrative purposes and need further refinements.

Development of optimal strategies in capacity expansion was discussed in this report with reference to incineration facilities. Assuming a given cost structure that has two components, one corresponding to fixed cost, and the other a variable cost component, the variation in incineration costs was studied under a 200-period finite planning horizon and an infinite planning horizon. Since the details of the mathematical derivations involved in the work were of purely theoretical value, they were not included in this report.

ANAEROBIC DIGESTION

Processing the garbage fraction of refuse through a conventional digester has been practiced for years, in that a sizeable amount of kitchen garbage is ground to the sewers each year by way of the home garbage disposal (grinder) unit. The concept that other organic fractions of refuse might also be reduced in volume and stabilized in this manner is, therefore, but one step beyond current practice. The use of anaerobic digestion is especially attractive when considered as an adjunct to the hydraulic transport of refuse.

The laboratory studies herein reported were designed to: 1) determine in terms of reduction in volatile solids the efficiency of anaerobic digestion when used to process the major individual organic constituents of the waste stream, namely paper, wood, green garbage, and animal manure; 2) ascertain the existence of any inhibitory effects, if any, attending the digestion of the fractions named under the preceding heading; 3) arrive at practical levels for the key operating parameters; and 4) assess the economic feasibility of the digestion of garbage alone and of the entire organic component of refuse. In the course of attaining these objectives, the kinetics of solid waste digestion received special attention.

In the experiments on the digestion of newspaper cellulose, 83% of the total cellulose in a mixture of 10% newspaper and 90% sewage sludge was destroyed with a detention period of 30 days. About 55% of the cellulose in the newspaper portion of the mixture was digested. With the proportion of newspapers stepped up to 20%, 73% of the total cellulose was destroyed, and 50% of the newspaper cellulose. Increasing the newspaper content of the mixture to 30% resulted in a 63% destruction of the total cellulose, and 42% of the newspaper cellulose. The composition of the gas from a digester receiving only raw sewage sludge was almost identical with that of gas produced by digesters receiving newspaper cellulose.

Grass clippings proved to be 73% digestible. The average destruction of the cellulose in the grass clippings amounted to 79%.

In experiments involving the digestion of manures, destruction of the volatile solids in chicken manure was about three times that of the solids in steer manure. Reduction in volume of the manures was minimal. Destruction of manure total solids was less than 15%. The composition of gas produced in the digestion of manures was quite like that of gas formed in the digestion of raw sewage sludge.

The results of the experiments indicate that the addition of wood to a digester would exert neither a chemically nor a physically adverse effect on the culture. Wood underwent very little decomposition in the digesters. In essence, the material acted as an inert material. Perhaps the imposition of detention periods longer than those applied in the present study might lead to the eventual decomposition of the wood.

In experiments involving the digestion of a "synthetic" refuse (components of the same nature and in same concentrations as found in municipal refuse), the total solids reduction averaged 44%; and volatile solids reduction, 52%. The calculated amount of destruction of the cellulose in the "synthetic" refuse was 55%. Gas production was about 56% that of digester receiving raw sewage sludge. No adverse effects were noted with the C:N ratio adjusted to a high of 48:1.

In a study on the kinetics of the destruction of cellulose in the "synthetic" refuse, minimum cell doubling time was calculated to be 5.8 days. The "wash-out" residence time for the digester cultures was found to be 7.8 days.

BIOFRACTIONATION

Work reported herein was concerned primarily with laboratory studies involving the fungus Trichoderma viride QM 6a and directed toward improving the yield of the enzyme cellulose, with a process design and economic evaluation of an enzymatic saccharification process based on the fungus. Laboratory results showed that the production of cellulose is favored when the pH level is at 5.0 and is inhibited at pH levels of 2.5 to 3.0. These results show that the rate of enzyme production is a function of fungus growth. The laboratory results also showed that cellulase production is enhanced by first growing the fungus rapidly on glucose and then introducing cellulose into the medium.

In making an economic analysis of the process, a basic plant and process design was drawn up. The plant was based on a waste cellulose feed of 10-ton/day. In the analysis, it was assumed that the material was delivered to the plant with all necessary pretreatment having been accomplished. Assigning a selling price of

$0.08/lb for the glucose produced in the operation, the net cost of processing a ton of cellulose in a 10-ton/day plant would be $130; and in a 100-ton/day plant, from a cost of $7/ton to a profit of $37/ton, depending upon whether or not the fermentors and hydrolysis vessel costs are scaled up directly with the remainder of the plant scale up according to the 0.6 power rule, or the entire plant is scaled up according to the 0.6 power rule.

PYROLYSIS-COMBUSTION

The construction phase of the Pyrolysis-Combustion portion of the overall research program was completed during the past year. Exploratory laboratory experiments were run with the use of sawdust to obtain information needed to serve as a guideline for experimentation involving the recently completed large-scale unit. Parameters to be studied with the large-scale unit are the physical condition of the feed, rate of feeding, mode of feeding, temperature of the reactor wall, temperature in the reactor, rate of gas recycle, and temperature of gas recycle.

WET OXIDATION

In the studies on wet oxidation, the first phase of the research program was completed. It involved the determination of the basic reaction relationships involved in the wet oxidation of raw white fir wood in the form of sawdust. Hydrolysis prevails when the process temperature is 160°C, as was indicated by the low volatilized carbon yields and oxygen consumption. At 220°C, oxidation substantially increased, as was shown by the higher volatilized carbon yields and oxygen consumption and by the lower dissolved solids yields. Yields of aldose monomers (glucose, mannose, xylose) were high at 160° to 180°C, but dropped off sharply with further increase in temperature. At 220°C, yields of the low carbon number aliphatic acids (e.g., acetic and formic acids) were dominant. Results of the work indicate that the oxidation step involves the dissolved rather than the residual solids.

APPENDICES

A. Application of Nigam's Algorithm

B. Waste Generation in the Nine-County San Francisco Bay Area

C. Remaining Capacity of Solid Waste Disposal Sites in the Nine-County San Francisco Bay Area

APPENDIX A

APPLICATION OF NIGAM'S ALGORITHM

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APPLICATION OF NIGAM'S[*] ALGORITHM

Let the current source set be designated as K and the number of sources in K be denoted by k. Then $K \subset P$, $|K| = k$, $k \leq \bar{\bar{m}} < |P|$. To start with K will be the empty set and $k = 0$. Let $r = \bar{\bar{m}} - k$.

Step A. The lower bound is established for each of the remaining potential source locations by using the formula

$$LB(h) = \sum_{j=1}^{n} \min_{\substack{i \notin K \\ i \neq h}} C_{ij} \quad \forall\ h \in P,\ h \notin K$$

Step B. These lower bounds are then arranged in decreasing order as DL(.) along with the source location they correspond to, which is stored as JL(.). The result is:

Source Location	JL(1)	JL(2)		JL(P-R)
Lower Bound	DL(1)	DL(2)		DL(P-R)

Step C. Source location from the list in (B) are cumulatively added to the set K to form new sets IS(.) with their lower bounds VS(.) as follows:

IS(.)	$K \cup JL(1)$	$K \cup JL(1) \cup JL(2)$	$K \cup JL(1) \cup JL(2) \ldots \cup JL(r-1)$
VS(.)	DL(1)	DL(2)	DL(r-1)

Note that the set IS(r-1) consists of (m-1) potential source locations, and that the lower bounds are still in decreasing order.

Step D. To find the r^{th} column in this IS(.) and VS(.) table, only one JL(.) source location is added at a time. Now and then the set of established sources S is also added on and an actual evaluation of the costs involved is done - instead of just finding a lower bound. Thus the sets considered for evaluation are:

$$K \cup JL(1) \cup JL(2) \cup \ldots \cup JL(r-1) \cup JL(r) \cup S$$

$$K \cup JL(1) \cup JL(2) \cup \ldots \cup JL(r-1) \cup JL(r-1) \cup S$$

$$\vdots$$

$$K \cup JL(1) \cup JL(2) \cup \ldots \cup JL(r-1) \cup JL(P-R) \cup S$$

In all these sets the total number of sources is exactly as desired, and the intent is to find an optimal solution rather than a feasible solution now. The source set having the lowest evaluation is chosen to fill the r^{th} column in (C) and the evaluated value is used as the lower bound value. This source set will be referred to as IIII and its evaluated value is VAL.

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Step E. For the sake of convenience, the IS(.) are rearranged so that they are now in increasing order, and VAL is checked against the previous worst acceptable solution available. The "previous worst acceptable solution" refers to an upper bound such that any source set with a higher evaluation is eliminated. (In the previous goaround the worst solution for the source set is retained as IWORDS(LY) with an evaluated value of VM). In the first process of course, there is no previous worst acceptable solution. If VAL is less than VM then the present evaluation is better and therefore is kept. If VAL is greater than VM, the previous worst acceptable solution is also regarded as the worst acceptable for this iteration, and is regarded as IIII and VAL, respectively.

Step F. All entries in IS(.) and VS(.) where the VS(.) exceeds the best current evaluation VAL are dropped from consideration.

Step G. The IS(.) and VS(.) are now fitted in their proper places in the master storage map IWORDS(.) and VALUES(.), respectively. The master storage map is kept so that VALUES(.) are in an increasing order. In the first iteration this master storage map is empty and so IS(.) and VS(.) will be allowed to fill in the first available places. In the later iterations they will be inserted at the proper places so that the increasing order of VALUES(.) is maintained.

Step H. All VALUES(.) in the master storage map greater than VAL are ignored so that the last entries in the map (indexed by LY) are IIII for the source set and VAL for the current evaluation. These are taken as IWORDS(LY) and VM for the next iteration as the worst possible cases from this iteration.

Step I. If there is only one source set left in the master storage map then that is the answer being sought, and the steps are terminated. If there are more than one source sets, the one with the greatest promise (and since they are arranged in increasing order it would be the first one) is chosen to serve as K for the next iteration, beginning with step (A).

APPENDIX B

WASTE GENERATION IN THE NINE-COUNTY SAN FRANCISCO BAY AREA

APPENDIX B

Table B-1 Development of Waste Generating Points and Corresponding Waste Generation (1966)

Table B-2 Population Estimates for the Nine-County San Francisco Bay Area

Table B-3 Updating Solid Waste Data from 1966 to 1968

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TABLE B-1

DEVELOPMENT OF WASTE GENERATING POINTS AND CORRESPONDING WASTE GENERATION (1966)

DSA Code and Name (1)	Solid Wastes Coming to All Sites in this DSA (tons/day) (2)	Solid Wastes Coming to Effective Sites in this DSA (tons/day) (3)	Population Section in this DSA (generating Point) (4)	Allocated to Generating Point Code Number (5)	Corresponding Population (6)	Solid Wastes Allocated to this Population Section (tons/day) (7)
0101 Berkeley	145	95	Berkeley (part)	58	116,270	93.7
			Oakland (part)	61	1,600	1.3
0102 Oakland	1,652	1,602	Oakland (part)	61	374,400	867.1
			Albany	57	17,100	39.8
			Emeryville	59	2,800	6.7
			Piedmont	60	11,400	26.4
			Hayward	66	89,700	207.7
			San Leandro	63	71,900	166.0
			Berkeley (part)	58	4,800	11.3
			San Leandro Area	63	19,750	45.8
			San Lorenzo	64	53,150	123.0
			Castro Valley	65	46,700	108.2
0103 Alameda	375	225	Alameda	62	69,200	225.0
0104 Fremont	275	275	Fremont	69	88,200	199.8
			Newark	68	22,200	50.4
			Union City	67	11,000	24.8
0105 Pleasanton	30	30	Pleasanton	70	8,100	11.9
			Upper Amador Valley	70	10,800	15.9
			Pleasanton Area	70	1,500	2.2
0106 Eastern Alameda	50	50	Livermore	71	29,000	46.2
			Livermore Area	71	2,400	3.8
0201 West Contra Costa	881	881	El Cerrito	45	27,850	109.1+
			Hercules	40	310	1.2
			Pinole	41	11,550	45.3
			Richmond	44	81,900	320.7
			San Pablo	43	23,250	90.8
			Corte Madera	51	8,171	32.1
			Belvedere	52	2,559	10.0
			Tiburon	52	4,978	19.5
			Mill Valley	53	11,783	46.2
			Sausalito	56	6,411	25.0
			Kensington	2/3 to 45	6,450	16.9
				1/3 to 57		8.4
			El Sobrante	42	21,000	82.3
			San Quentin	54	4,720	18.4
			Strawberry Alto	1/3 to 51	5,571	7.3
				1/3 to 53		7.3
				1/3 to 55		7.3
			Homestead Valley	2/3 to 53	6,414	16.7
				1/6 to 51		4.2
				1/6 to 55		4.2
			Marin City	55	2,114	8.2
0202 Central Contra Costa	432	430	Clayton	27	1,023	1.7
			Concord	31	75,600	126.3
			Martinez	29	12,450	20.8
			Pleasant Hill	32	27,087	45.3
			Walnut Creek	33	23,328	38.8
			Port Chicago	28	2,920	4.8
			West Pittsburgh	26	9,900	16.5
			Lafayette	36	18,000	30.3
			Pacheco	30	6,400	10.7
			Alamo-Danville	1/2 to 34	12,000	10.4
				1/2 to 35		10.4
			Rodeo	39	7,140	12.1
			Orinda	38	14,850	24.7
			Moraga	37	9,800	16.5
			Walnut Creek Area	33	29,772	49.7
			Martinez Area	29	6,670	11.0
0203 East Contra Costa	215	215	Antioch	25	23,050	106.9
			Brentwood	24	2,415	11.3
			Pittsburgh	26	20,900	96.8
0301 West Marin	9.6	9.6	Tamalpais Valley	1/2 to 48	3,200	4.8
				1/2 to 46		4.8

TABLE B-1 (Continued)

DSA Code and Name (1)	Solid Wastes Coming to All Sites in this DSA (tons/day) (2)	Solid Wastes Coming to Effective Sites in this DSA (tons/day) (3)	Population Section in this DSA (4)	Allocated to Generating Point Code Number (5)	Corresponding Population (6)	Solid Wastes Allocated to this Population Section (tons/day) (7)
0302 East Marin	190.4	190.4	Fairfax	48	7,201	10.9
			Larkspur	51	7,858	11.0
			Novato	46	25,932	39.3
			Ross	50	2,680	4.0
			San Anselmo	49	13,233	20.0
			San Rafael	47	32,771	49.7
			Novato-Hamilton	46	6,365	9.6
			North of San Rafael	47	18,774	28.4
			Ross Valley-Kentfield	1/4 to 50	10,956	4.2
				3/4 to 51		12.5
0401 Napa	183	183	Calistoga	11	1,895	3.3
			Napa	8	30,231	53.3
			St. Helena	10	3,482	6.1
			Yountville	9	2,372	4.2
			Vallejo	6	65,826	116.1
0500 San Francisco	2,699	2,580	Richmond	105	90,540	312.5
			Marina-Pacific Heights	106	67,100	231.6
			Central	106	93,295	322.0
			South of Market	108	28,260	97.6
			Western Addition	109	52,815	182.3
			Twin Peaks-Buena Vista	110	63,025	217.6
			South Van Ness	111	43,570	150.3
			Potrero-Bayshore	112	45,800	158.0
			Outer Mission	113	83,000	286.6
			South Freeway-Mt. Davidson	114	58,075	200.3
			Lake Merced	115	29,620	102.3
			Sunset	116	92,400	318.9
0601 Daly City	89	89	Daly City (part)	72	54,400	82.9
			South San Francisco (part)	76	3,500	5.2
			Colma	73	500	0.9
0602 South San Francisco	395	395	South San Francisco (part)	76	38,500	148.6
			Daly City (part)	72	6,100	23.5
			Brisbane	75	3,070	11.9
			Millbrae	78	20,000	77.2
			San Bruno (part)	77	25,200	97.3
			Burlingame (part)	79	9,450	36.5
0603 Pacifica	60	60	Pacifica	74	29,800	44.9
			San Bruno (part)	77	10,000	15.1
0604 Central San Mateo	710	710	Burlingame (part)	79	17,600	49.8
			Atherton	84	8,350	23.7
			Belmont	81	23,050	64.7
			Hillsborough	79	8,625	24.5
			Half Moon Bay	88	3,150	9.0
			Menlo Park	85	29,800	84.4
			Redwood City	83	56,700	160.5
			San Carlos	82	25,100	71.1
			San Mateo	80	78,600	222.3
0701 Palo Alto	175	175	Palo Alto	89	55,284	175.0
0702 Mountain View	170	170	Mountain View	92	48,503	170.0
0703 Sunnyvale	256	256	Sunnyvale (part)	93	76,201	256.0
0704 Gilroy	36	36	Gilroy	104	10,258	24.9
			Morgan Hill	103	4,566	11.1
0705 Los Gatos	370	370	Los Gatos (part)	97	14,289	44.9
			Saratoga	95	21,944	69.0
			Monte Sereno	96	2,066	6.7
			Campbell (part)	98	14,011	44.2
			San Jose (part)	100	65,100	205.2

TABLE B-1 (Continued)

DSA Code and Name (1)	Solid Wastes Coming to All Sites in this DSA (tons/day) (2)	Solid Wastes Coming to Effective Sites in this DSA (tons/day) (3)	Population Section in this DSA (4)	Allocated to Generating Point Code Number (5)	Corresponding Population (6)	Solid Wastes Allocated to this Population Section (tons/day) (7)
0706 Los Altos	570	570	Los Altos	91	23,793	90.9
			Los Altos Hills	90	5,825	22.3
			Cupertino	94	12,043	45.7
			Santa Clara	99	82,482	314.9
			San Jose (part)	100	14,364	54.8
			Woodside	86	4,156	15.8
			Portola Valley	87	5,370	20.5
			Alviso	101	1,312	5.1
0707 San Jose	1,005	1,005	San Jose (part)	100	280,138	879.5
			Milpitas	102	19,834	62.3
			Sunnyvale (part)	93	8,623	27.0
			Los Gatos (part)	97	4,312	13.5
			Campbell (part)	98	7,210	22.7
0801 Vacaville	78	78	Vacaville	2	15,243	62.6
			Dixon	1	3,748	15.4
0802 Fairfield	127	122	Fairfield	3	25,007	77.8
			Benicia	5	6,612	20.6
			Suisun City	3	3,861	12.0
			Rio Vista	7	3,168	9.8
			Cordelia	4	602	1.8
0901 Healdsburg	63	63	Healdsburg	20	5,280	36.9
			Cloverdale	22	3,260	22.7
			Geyserville	21	500	3.4
0902 Santa Rosa	181	179	Santa Rosa	17	44,010	175.0
			Fulton	18	500	2.0
			Windsor	19	500	2.0
0903 Western Sonoma	47.3	46.3	Jenner	23	767	46.3
0904 Southern Sonoma	140	140	Cotati	15	1,400	5.8
			Petaluma	12	20,500	84.8
			Rohnert Park	15	4,490	18.5
			Sonoma	13	3,725	15.3
			Sebastapol	16	3,260	13.5
			Penngrove	14	502	2.1

TABLE B-2

POPULATION ESTIMATES FOR THE NINE-COUNTY SAN FRANCISCO BAY AREA

County	July 1966 Estimate[a]	July 1968 Estimate[b]	Population Ratio (1968/1966)
Alameda	1,045,000	1,150,000	1.10048
Contra Costa	528,400	604,998	1.14496
Marin	195,300	231,999	1.18791
Napa	76,800	87,000	1.13281
San Francisco	737,300	759,909	1.03067
San Mateo	539,300	600,000	1.11255
Santa Clara	925,000	1,033,000	1.11675
Solano	162,600	180,003	1.10701
Sonoma	182,900	222,002	1.21378

[a] "California Population, 1967," Department of Finance, State of California, Sacramento, California, October 1967.

[b] "Population and Labor Force Projections," Supplemental Report R & A-2; Association of Bay Area Governments, Claremont Hotel, Berkeley, California.

TABLE B-3

UPDATING SOLID WASTE DATA FROM 1966 TO 1968

Generating Point Name (1)	Generating Point Code Number (2)	Solid Wastes Produced as of July 66 (tons/day) (3)	Ratio (4)	Solid Wastes Produced Estimated as of July 68 (tons/day) (5)
Dixon	1	15.4	1.10701	17.0
Vacaville	2	62.6	1.10701	69.3
Fairfield and Suisun	3	89.8	1.10701	99.4
Cordelia	4	1.8	1.10701	2.0
Benicia	5	20.6	1.10701	22.8
Vallejo	6	116.1	1.10701	128.5
Rio Vista	7	9.8	1.10701	10.9
Napa	8	53.3	1.13281	60.4
Yountville	9	4.2	1.13281	4.8
St. Helena	10	6.1	1.13281	6.9
Calistoga	11	3.3	1.13281	3.7
Petaluma	12	84.8	1.21373	102.9
Sonoma	13	15.3	1.21378	18.6
Penngrove	14	2.1	1.21378	2.5
Cotati and Rohnert Park	15	24.3	1.21378	29.5
Sebastapol	16	13.5	1.21378	16.4
Santa Rosa	17	175.0	1.21378	212.4
Fulton	18	2.0	1.21378	2.4
East and West Windsor	19	2.0	1.21378	2.4
Healdsburg	20	36.9	1.21378	44.8
Geyserville	21	3.4	1.21378	4.1
Cloverdale	22	22.7	1.21378	27.5
Jenner	23	46.3	1.21378	56.2
Brentwood	24	11.3	1.14496	12.9
Antioch	25	106.9	1.14496	122.4
Pittsburg	26	113.3	1.14496	129.7
Clayton	27	1.7	1.14496	2.0
Port Chicago	28	4.8	1.14496	5.5
Martinez	29	31.8	1.14496	36.4
Pacheco	30	10.7	1.14496	12.2
Concord	31	126.3	1.14496	144.6
Pleasant Hill	32	45.3	1.14496	51.9
Walnut Creek	33	88.5	1.14496	101.3
Alamo	34	10.4	1.14496	11.9
Danville	35	10.4	1.14496	11.9
Lafayette	36	30.3	1.14496	34.7
Moraga	37	16.5	1.14496	18.9
Orinda	38	24.7	1.14496	28.3
Rodeo	39	12.1	1.14496	13.9
Hercules	40	1.2	1.14496	1.4
Pinole	41	45.3	1.14496	51.9
El Sobrante	42	82.3	1.14496	94.2
San Pablo	43	90.8	1.14496	104.0
Richmond	44	320.7	1.14496	367.2
El Cerrito	45	126.0	1.14496	144.3
Novato	46	53.7	1.18791	63.8
San Rafael	47	78.1	1.18791	92.8
Fairfax	48	15.7	1.18791	18.6
San Anselmo	49	20.0	1.18791	23.7
Ross	50	8.1	1.18791	9.6
Larkspur-Corte Madera	51	68.0	1.18791	80.8
Tiburon-Belvedere	52	29.5	1.18791	35.0
Mill Valley	53	70.3	1.18791	83.5
San Quentin	54	18.4	1.18791	21.9
Marin City	55	19.7	1.18791	23.4
Sausalito	56	25.0	1.18791	29.7
Albany	57	48.2	1.10048	53.0
Berkeley	58	105.0	1.10048	115.6
Emeryville	59	6.7	1.10048	7.4

TABLE B-3 (Continued)

Generating Point Name (1)	Generating Point Code Number (2)	Solid Wastes Produced as of July 66 (tons/day) (3)	Ratio (4)	Solid Wastes Produced Estimated as of July 68 (tons/day) (5)
Piedmont	60	26.4	1.10048	29.0
Oakland	61	868.4	1.10048	955.7
Alameda	62	225.0	1.10048	247.6
San Leandro	63	211.8	1.10048	233.1
San Lorenzo	64	123.0	1.10048	135.4
Castro Valley	65	108.2	1.10048	119.1
Hayward	66	207.7	1.10048	228.6
Union City	67	24.8	1.10048	27.3
Newark	68	50.4	1.10048	55.5
Fremont	69	199.8	1.10048	219.9
Pleasanton	70	30.0	1.10048	33.0
Livermore	71	50.0	1.10048	55.0
Daly City	72	106.4	1.11255	118.4
Colma	73	0.9	1.11255	1.0
Pacifica City	74	44.9	1.11255	50.0
Brisbane	75	11.9	1.11255	13.2
South San Francisco	76	153.8	1.11255	171.1
San Bruno	77	112.4	1.11255	125.1
Millbrae	78	77.2	1.11255	85.9
Burlingame-Hillsborough	79	110.8	1.11255	123.3
San Mateo	80	222.3	1.11255	247.3
Bellmont	81	64.7	1.11255	72.0
San Carlos	82	71.1	1.11255	79.1
Redwood City	83	160.5	1.11255	178.5
Atherton	84	23.7	1.11255	26.4
Menlo Park	85	84.4	1.11255	93.9
Woodside	86	15.8	1.11255	17.6
Portola Valley	87	20.5	1.11255	22.8
Half Moon Bay	88	9.0	1.11255	10.0
Palo Alto	89	175.0	1.11675	195.4
Los Altos Hills	90	22.3	1.11675	24.9
Los Altos	91	90.9	1.11675	101.5
Mountain View	92	170.0	1.11675	189.9
Sunnyvale	93	283.0	1.11675	316.0
Cupertino	94	45.7	1.11675	51.0
Saratoga	95	69.0	1.11675	77.1
Monte Sereno	96	6.7	1.11675	7.5
Los Gatos	97	58.4	1.11675	65.2
Campbell	98	66.9	1.11675	74.7
Santa Clara	99	314.9	1.11675	351.7
San Jose	100	1139.5	1.11675	1272.5
Alviso	101	5.1	1.11675	5.7
Milpitas	102	62.3	1.11675	69.6
Morgan Hill	103	11.1	1.11675	12.4
Gilroy	104	24.9	1.11675	27.8
Richmond (SF)	105	312.5	1.03067	322.1
Marina-Pacific Heights (SF)	106	231.6	1.03067	238.7
Central (SF)	107	322.0	1.03067	331.9
South of Market (SF)	108	97.6	1.03067	100.6
Western Addition (SF)	109	182.3	1.03067	187.9
Twin Peaks-Buena Vista (SF)	110	217.6	1.03067	224.3
South Van Ness (SF)	111	150.3	1.03067	154.9
Potrero-Bayshore (SF)	112	158.0	1.03067	162.9
Outer Mission (SF)	113	286.6	1.03067	295.4
South Freeway-Mt. Davidson (SF)	114	200.3	1.03067	206.4
Lake Merced (SF)	115	102.3	1.03067	105.4
Sunset (SF)	116	318.9	1.03067	328.8

APPENDIX C

REMAINING CAPACITY OF SOLID WASTE DISPOSAL SITES IN THE NINE-COUNTY SAN FRANCISCO BAY AREA

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TABLE C-1

REMAINING CAPACITY OF SOLID WASTE DISPOSAL SITES IN THE NINE-COUNTY SAN FRANCISCO BAY AREA

Site No. (1)	Site Name and Identification (2)	Remaining Capacity as of 1966 (acre-feet) (3)	Average Waste Received at Site (tons/day) (4)	Remaining Capacity as of 1968 (acre-feet) (5)
1	Ox Mountain Site EE in San Mateo County	-	-	18,500
2	Benicia in Solano County	-	-	15,000
3	East of Milpitas-Customer Utility Site	-	-	1,000
4	Expansion of West Winton-Oakland Scavenger Site (19)	-	-	15,000
5	Expansion of Durham Road-Oakland Scavenger Site (21)	-	-	15,000
6	Expansion of Eastern Alameda County Site (22)	-	-	15,000
7	Expansion of Acme Fill Site (26)	-	-	15,000
8	Expansion of West Contra Costa County Site (27)	-	-	15,000
9	Expansion of Redwood Site (28)	-	-	15,000
10	Expansion of American Canyon Site (34)	-	-	15,000
11	Expansion of San Mateo Scavenger Company Site (41)	-	-	15,000
12	Expansion of Palo Alto Site (48)	-	-	15,000
13	Expansion of Newby Island Site (54)	-	-	15,000
14	Expansion of B and J Site (67)	-	-	15,000
15	Albany	1,550	165	1,383
16	Berkeley	120	95	24
	Alameda	100	225	-
17	Davis Street-Oakland Scavenger Co.	4,300	975	3,311
18	San Leandro Marina	670	60	609
19	West Winton-Oakland Scavenger Co.	14,700	400	14,295
20	Turk Island Company	770	25	745
21	Durham Road-Oakland Scavenger Co.	6,950	250	6,696
22	Eastern Alameda County	8,500	50	8,449
23	Pleasanton	450	30	420
24	Pittsburg	360	105	254
25	Antioch	400	110	288
26	Acme Fill	33,600	430	33,164
27	West Contra Costa County	13,600	880	12,708
28	Redwood	7,200	135	7,063
29	San Quentin	100	60	39
30	Martinelli	1,900	5	1,895
31	Upper Valley	400	10	390
32	Yountville Veterans Home	55	13	42
33	Napa State Hospital	14	2	12
34	American Canyon	5,300	90	5,209
35	Del Santi	15	1	14
	Islais Creek	800	900	-
36	Hunter's Point NSY	400	40	359
37	Leonetti	25	10	15
38	Sanitary Fill Co.	2,100	1,600	479
	South San Francisco	100	280	-
39	Burlingame Rubbish	215	100	114
40	San Mateo Rubbish	400	100	299
41	San Mateo Scavenger Co.	2,040	400	1,635
42	South County Disposal District	240	200	37
43	Colma Rubbish	100	15	85
44	Daly City-Mussel Rock	190	79	110
45	Pacifica	800	60	739
46	Half Moon Bay Rubbish	12	3	9
47	Pascedero	13	5	8
48	Palo Alto	2,500	175	2,323
49	Mountain View	300	90	209

NOTE: Sites 1 through 14 are potential sites used in this study. As such there are no wastes going to site at the moment.

TABLE C-1 (Continued)

Site No. (1)	Site Name and Identification (2)	Remaining Capacity as of 1966 (acre-feet) (3)	Average Waste Received at Site (tons/day) (4)	Remaining Capacity as of 1968 (acre-feet) (5)
50	Sterlin Road Green Valley	160	80	79
51	Sunnyvale	1,100	250	847
52	Santa Clara	750	70	679
	Edgewater	30	200	-
53	Los Altos Ranch	1,600	300	1,296
54	Newby Island	5,200	500	4,693
	Customer Utility	45	55	-
	Story Road	30	160	-
55	Singleton Road	280	40	239
	San Jose	60	150	-
56	Eastside	200	100	99
57	Guadalupe	1,200	370	825
58	Morgan Hill	400	10	390
59	Moffett Field NAS	280	6	274
60	Pacheco Pass	1,120	10	1,110
61	Gilroy	1,140	10	1,130
62	Mare Island NSY	336	54	281
63	Travis AFB	86	37	49
64	Fairfield	925	48	876
65	Solano County	500	25	475
66	Dixon	145	15	130
67	B and J	2,040	60	1,979
68	Rio Vista	128	12	116
69	Sonoma	300	93	206
70	Petaluma	120	3	117
71	Cloverdale	20	7	13
	Windsor	15	173	-
72	Guerneville	850	35	815
73	Occidental	25	20	5
74	Roblar	650	40	609

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